CONTROLS IN SEDIMENTATION
FROM A STUDY OF SEDIMENT GEOMETRY

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Thesis presented for the degree of DOCTOR OF PHILOSOPHY

UNIVERSITY OF EDINBURGH 1969

ABSTRACT

The WESTPHALIAN coal-bearing successions of central England provide an excellent opportunity for investigating the controls which govern the accumulation of shallow water sediments. Classical and statistical studies, supplemented by a deterministic model of compaction, suggest that the principal large scale control was DOWNWARPING of the Pennine Basin, and that the principal moderate scale control was by the DEPOSITIONAL ENVIRONMENT, which was dominated by the location of BARRIER SAND BARS and catalysed by the unstable compaction of PEAT. Tectonism, differential compaction, delta distributary-switching and the breaking of barrier bars probably made no significant contribution to the development of the sedimentary sequences of the East Midlands Coalfield, England.

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ERRATA

page 36 for Middleton(1967) read Lee and Middleton(1967)

page 163 for Clarke(1957) read Davies(1957)

INTRODUCTION

In 1859 Hall's discovery that the sedimentary rocks in the Appalachian fold belt were much thicker than their time equivalents elsewhere, led to the concept of the geosyncline and sparked off a controversy regarding the forces that control the development of thick rock successions. Hall considered that subsidence in these belts was caused by the weight of the accumulated sediment because, in his opinion, most of the Appalachian rocks had been deposited in shallow water. Dana, in 1873, could not bring himself to accept this hypothesis and put forward a counter proposal, that the sediments were laid down where space had previously been created to accommodate them.

While the foraminiferal studies of Manley Natland (see Shepard 1959) showed that Dana was correct in at least some of the cases, there are many instances of thick successions which were undoubtedly accumulated at sea level. The Coal Measures of the Carboniferous System is one of these instances. According to Kuenen (1950), "Troughs now containing coal fields were maintained above sea level by sedimentation, except for short marine ingressions, while the floor gradually subsided." There is no reason at present to doubt this hypothesis, and the Coal Measures can be considered to have been accumulated on a labile shelf (von Bubnoff 1963) or in a parageosyncline (Schuchert 1923). The absence of severe tectonic deformation supports the parageosyncline concept.

If the sediments of the Coal Measures were accumulated at 'sea level' the successions must have been emplaced by subsidence concurrent but not necessarily coincident with deposition. What caused this subsidence? Hall's loading hypothesis has been criticised (e.g. Grabau 1924, Umbgrove 1947) for reasons based primarily on the supposed density difference between mantle and crust. To use Holmes' (1965) words, "..... from a standpoint of isostasy ..... while yielding of the crust under a growing load of marine sediment undoubtedly occurs, the total effect is strictly limited."

The motivation of subsidence by loading has regained some favour in recent years with the discovery that the isostasy difficulties can be overcome if eclogite is generated at the base of the crust under increasing pressure. Collette (1968) suggested that under these conditions subsidence can be considered to be entirely controlled by loading. A different hypothesis, recently put forward by Bott (1965), can be used to explain the control of deposition by subsidence in parageosynclines, where it is impossible to invoke compressive stresses (Vening Meinesz 1940) because of the absence of subsequent severe tectonic deformation. According to Bott(1965), highland uplift, which is caused by erosion, gives rise to ductile flow in the upper mantle which in turn gives rise to acute local subsidence in adjacent basins, manifested in the form of elastic deformation or faulting.

Whatever the geophysical or geochemical intricacies of the proposed mechanisms the basic question still remains to be answered:

is subsidence caused by sediment loading or does subsidence make room for incoming sediments?

Moving from the large to the small scale, one of the most conspicuous features of coal-bearing successions is the repetitive nature of the sediments (Duff et al 1967). Speculation regarding the controlling mechanisms of cyclicity has led to a wide range of hypotheses. Mechanisms which operate on a scale greater than the basin of deposition have been proposed, and include crustal movements, eustatic changes in sea-level, climatic variations and even astronomical factors. Suggested controls operative within the basin have included compaction, delta switching or channel wandering, edaphic factors and local tectonics. The internal and self-activating mechanisms have gained favour in recent years (Oertel and Walton 1967).

The features which can be observed in Coal Measures successions are probably the result of the interaction of these and other controls operating on unknown scales with unknown intensities. The detail in which the stratigraphy of the Coal Measures is known, however, makes them most suitable for an attempt to sort out the imbroglio of controls. Ultimately it should be possible to construct models which approximate to the environments in which coal-bearing successions were deposited.

Most geological problems are tackled using argument by analogy of the past with the present; this thesis is no exception. It is easy to introduce illogicalities into arguments of this type. For example, if a modern process produces a response which can also be observed in ancient deposits, then it is illogical to equate the modern and ancient processes, without further investigation to show that the response in question could not be, nor ever have been, produced by some other means. In this thesis, the projection in time of observations made in the Recent has been attempted by means of the premises listed in table (1.0.1).

The substantive truth of the projection depends on the probability that the premises are geologically faulty; as stated by Simpson (1963), "... the essential point is determination of the probability of the premises themselves and mathematics and logic only provide methods for correctly arriving at the implications contained in these premises." Although it may be possible to establish the substantive truth of premise 'Y' in table (1.0.1), premise 'X' is influenced both by evolution and by diagenesis. In addition, the probability that many (if not almost all) ancient environments are not present in Recent times makes it almost impossible to assess the truth content of premise 'Z'. On the other hand, some physical processes are not time dependent. Thus, although individual parameters may vary, the overall features produced by processes of this type will be the same today as throughout geological time.

In order to estimate the probabilities that go towards the construction of a logical argument, it is necessary to supplement critical geological reasoning with enumeration and quantitative statistical assessment. For example, only if the actual probabilities of the truth of two statements are known can the probability of their conjunction be considered.

Some quantitative applications may be criticised on account of the 'low powered' interpretations offered for 'high powered' techniques. The cause often appears to stem from a failure to define the problem

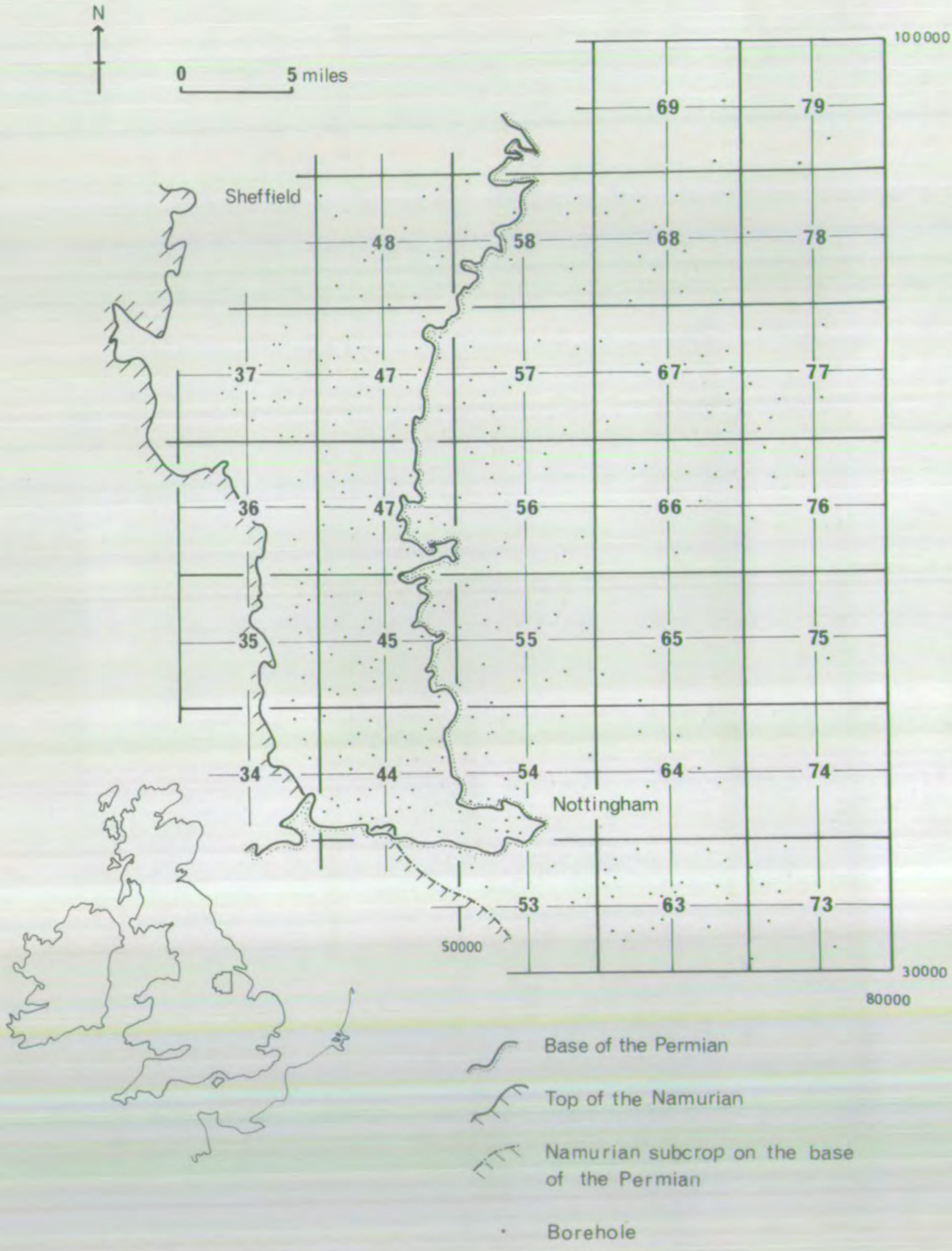
(i)	Premise X	Environments (A) and their characteristics (B) are invariant with time.
	Premise Y	Environment (A) produces character set (B) and no other.
	Premise Z	Character set (B) cannot be formed in any other environment than (A).

Table(1.0.1). (i) Premises for the backward projection in time of inference from Recent sediments.

accurately or set up hypotheses which can be tested in some rigorous manner. Consequently, mathematical techniques are employed to emphasize some feature rather than to make or prove a particular point.

In response to these criticisms, the mathematical techniques used subsequently have been critically examined, and have been applied only under well-defined conditions. The simple positive or negative results obtained in this way have a known probability of being in error. It is hoped that the results obtained can, therefore, be considered truly objective and reproducible.

This thesis describes an attempt to isolate the responses to different processes in the coal-bearing rocks of the Westphalian of Central England. An effort has been made to identify the processes from the responses in a logical fashion, using the principle of uniformitarianism. Wherever possible, quantitative techniques have been used to maintain objectivity and to provide some measure of the probability of error in the various observations and, therefore, in the conclusions that are ultimately derived from them.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Nottingham
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50000
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80000
Base of the Permian
Top of the Namurian
Namurian subcrop on the base of the Permian
Borehole

Figure(2.0.1)

DATA

The data used in the present study are from that part of the East Pennine Coalfield of Great Britain included by the East Midlands division of the National Coal Board. Mr. G. Armstrong, chief geologist of the National Coal Board, kindly gave permission for the collection of subsurface information, and Mr. R. E. Elliott, regional geologist, kindly provided facilities at the East Midlands Geological Outstation of the National Coal Board at Arnold near Nottingham.

The study area, figure (2.0.1), covers approximately 1348 square miles (3500 square kilometres), extending about 31 miles (50 kilometres) in an East-West direction and 43.5 miles (70 kilometres) North-South. The minimum irregular area containing all the data collection points covers an area of 730 square miles (1900 square kilometres).

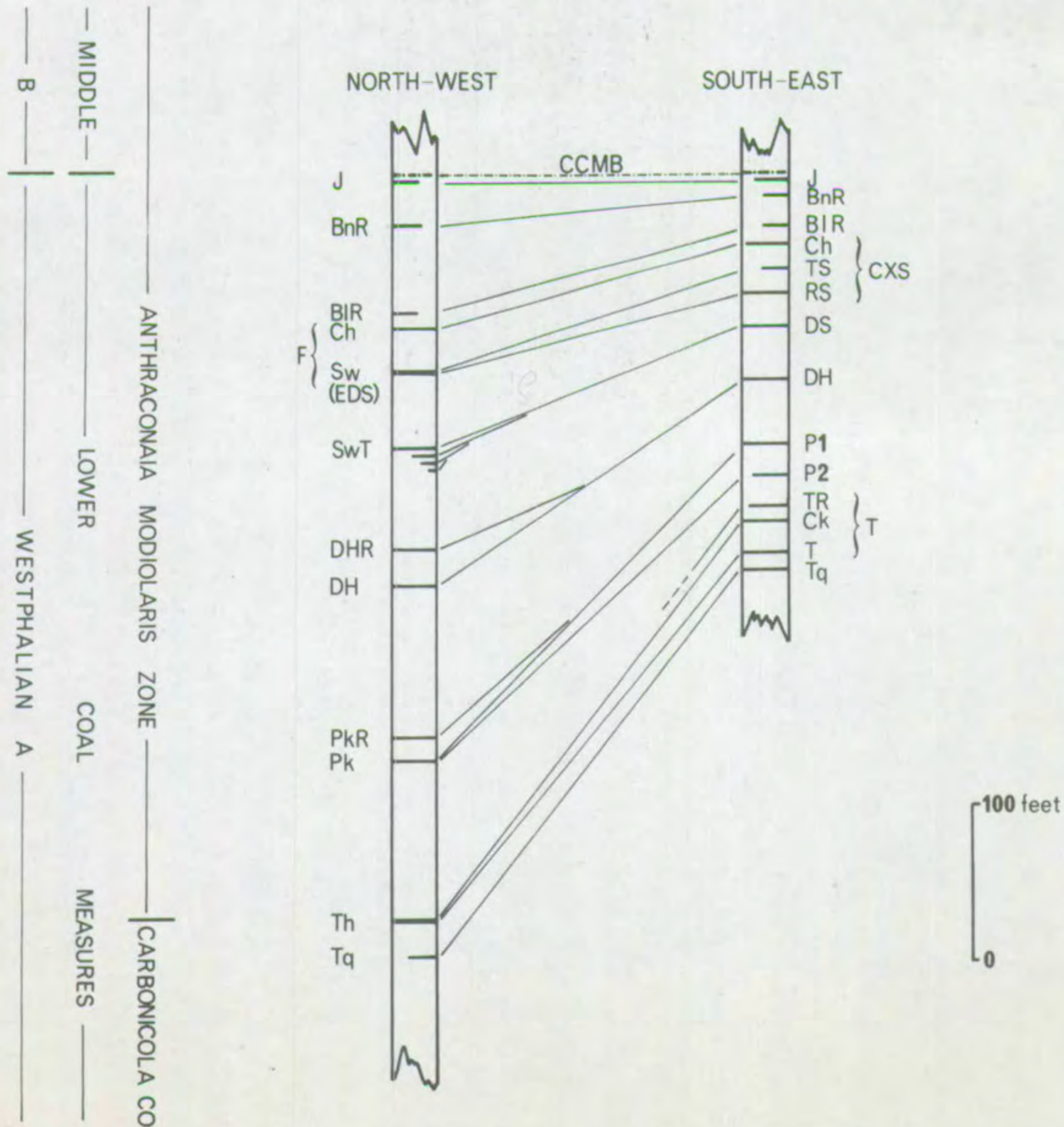
Previous work in this area has had an economic bias (Edwards 1935, 1951, 1954, 1967, Wills 1956, Eden <u>et al</u> 1957, Smith <u>et al</u> 1967) but more recently the detailed sedimentology has been studied by Elliott (1965, 1968, 1969). The previous work on the Coal Measures fauna is listed in the bibliography given by Calver (1968), who has personally studied the distribution of the marine fauna. Quantitative investigations into the development of the Coal Measures sediments have been carried out by Duff and Walton (1962, 1964).

The present investigation was restricted to the section of strata between the Threequarters Coal, of upper Communis age, and the Clay Cross Marine Band, of middle Modiolaris age, because it was found to be described in the largest number of more recent borehole records. In all, 306 records of boreholes were used, giving an area of 6 square kilometres for each data collection locality. Although the boreholes are reasonably evenly distributed, they are more numerous, and in general older, in the West than in the East.

The exact locations of all the boreholes employed are listed in appendix (II) but a coding scheme, which is used throughout the text, enables their approximate position to be located in figure (2.0.1). The first two digits, of the five-digit code, refer to the Ordnance Survey 1:25000 sheet reference numbers, and thus to 10 kilometre National Grid squares. The third digit is 1, 2, 3, or 4 according to whether the borehole is located in the South-West, South-East, North-West or North-East quadrant of the grid square. The fourth and fifth digits identify the individual record. For example, 45114 refers to the 14th borehole record in the South-West quadrant of grid square SK45.

Details of the problems of coal correlations are given in the appropriate parts of section (4). However, the correlation scheme employed is shown in figure (2.0.2), together with the stratigraphic location of the section under consideration. For the sake of clarity, the coals of the section of strata under investigation have been identified in abbreviated form in subsequent figures and diagrams. A list of the abbreviations employed is given in table (2.0.3).

The subsurface information consists of reports of subjective appraisals of rocks encountered during drilling by geologists and others


NORTH-WEST
SOUTH-EAST
CCMB
J
BnR
BIR
Ch
F
Sw
(EDS)
SwT
DHR
DH
PkR
Pk
Th
Tq
J
BnR
BIR
Ch
TS
RS
CXS
DS
DH
P1
P2
TR
Ck
T
Tq
T
100 feet
0
ANTHRACONAIA MODIOLARIS ZONE
CARBONICOLA COMMUNIS
MIDDLE
LOWER COAL MEASURES
B
WESTPHALIAN A

Figure(2.0.2)

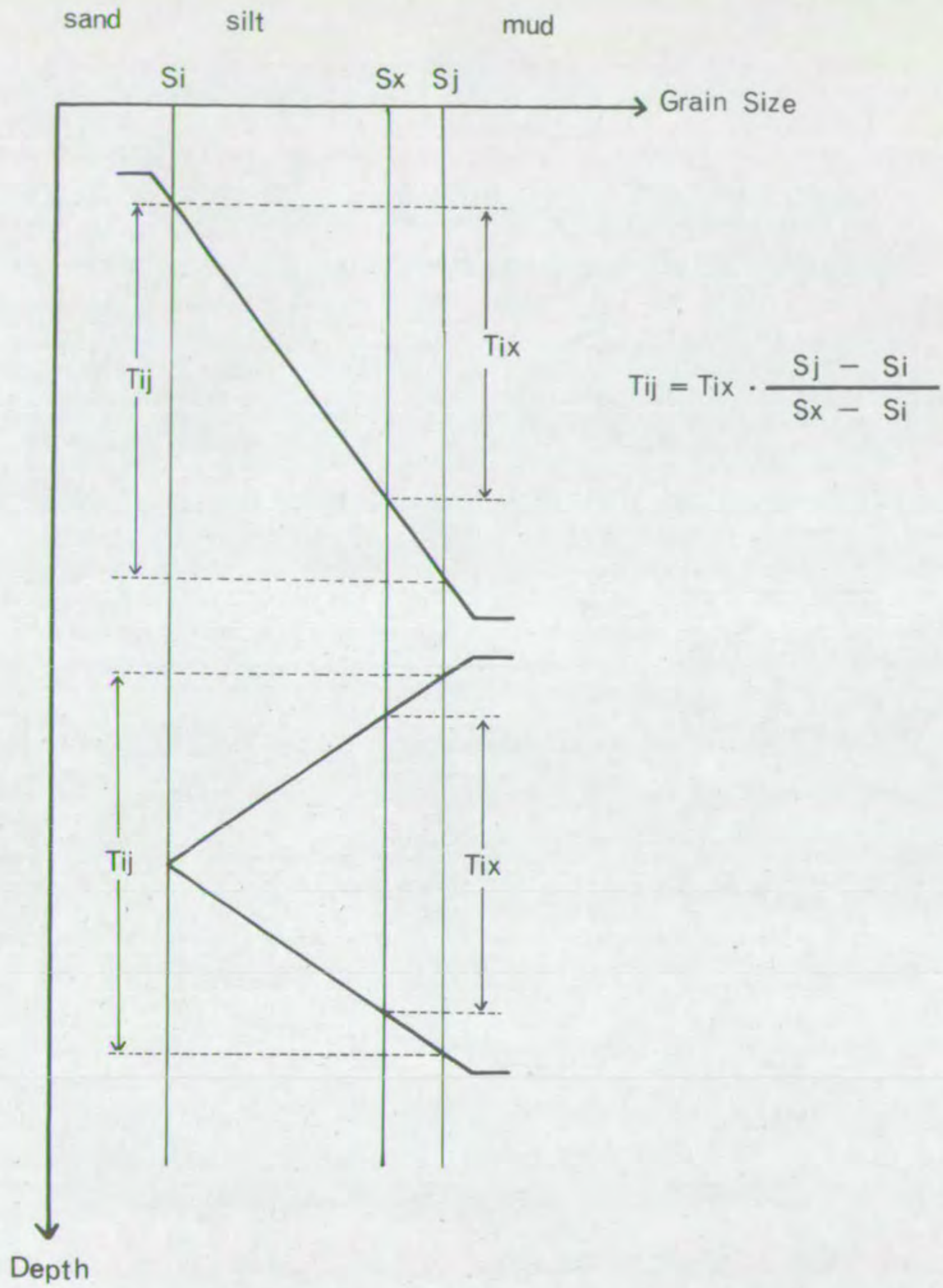
Abbreviation	Full Name
CCMB	Clay Cross Marine Band
J	Joan coal
BnR	Brown Rake coal
BlR	Black Rake coal
Ch	Chavery coal
TS	Top Soft coal
RS	Roof Soft coal
Sw	Sitwell coal
CXS	Clay Cross Soft coal (group)
F	Flockton coal
EDS	Eckington Deep Soft coal
DS	Deep Soft coal
SwT	Sitwell Thin coal
DHR	Deep Hard Rider coal
DH	Deep Hard coal
P1	First Piper coal
P2	Second Piper coal
Pk	Parkgate coal R rider
TRf	Tupton Roof coal
Ck	Cockleshell coal
T	Tupton coal
Th	Thorncliffe coal
Tq	Threequarters coal

Table(2.0.3) List of abbreviations of coal names used in subsequent figures and tables.

and, therefore, is subject to operator variance (Griffiths et al 1954). It has been shown (Elliott 1968, written communication) that while currently active, trained geologists agree about the distinctions of siltstones and sandstones, the position of the siltstone to mudstone or shale transition is a matter for debate.

Differing opinions concerning the location of this grain size boundary lead to different thickness estimates when sequences of silt and mud are being described. It is possible to estimate the amount of error, arising from this source, in borehole sections with continuous and regular fluctuations in grain size with depth. The scheme includes the situation most prone to error, where a siltstone is progressively reduced in grain size and grades up and down into mudstone, figure (2.0.4). Using average values of 30 and 5 microns, for the sandstone/siltstone and siltstone/mudstone boundaries respectively, and the results of an experiment (Elliott 1968, written communication), in which different geologists described a standard set of samples, the error in thickness of a bed of siltstone, and the contiguous bed(s) of shale or mudstone, can be shown to amount to as much as 30%.

Older records, which are often described in terminology which is now defunct, are subject to unknown sources of error. No compensation has, therefore, been made for known bias because borehole logs written by geologists, who took part in the experiment, constitute only a small fraction of the total. However, operator variance cannot be ignored. The principal expression of this source of error is on the scale of an individual borehole and anomalies, arising in the areal distribution of some measured characteristic on this scale alone, must not be taken to be of any geological significance.



Figure(2.0.4) The effect of grain size classification errors on thickness measurements.

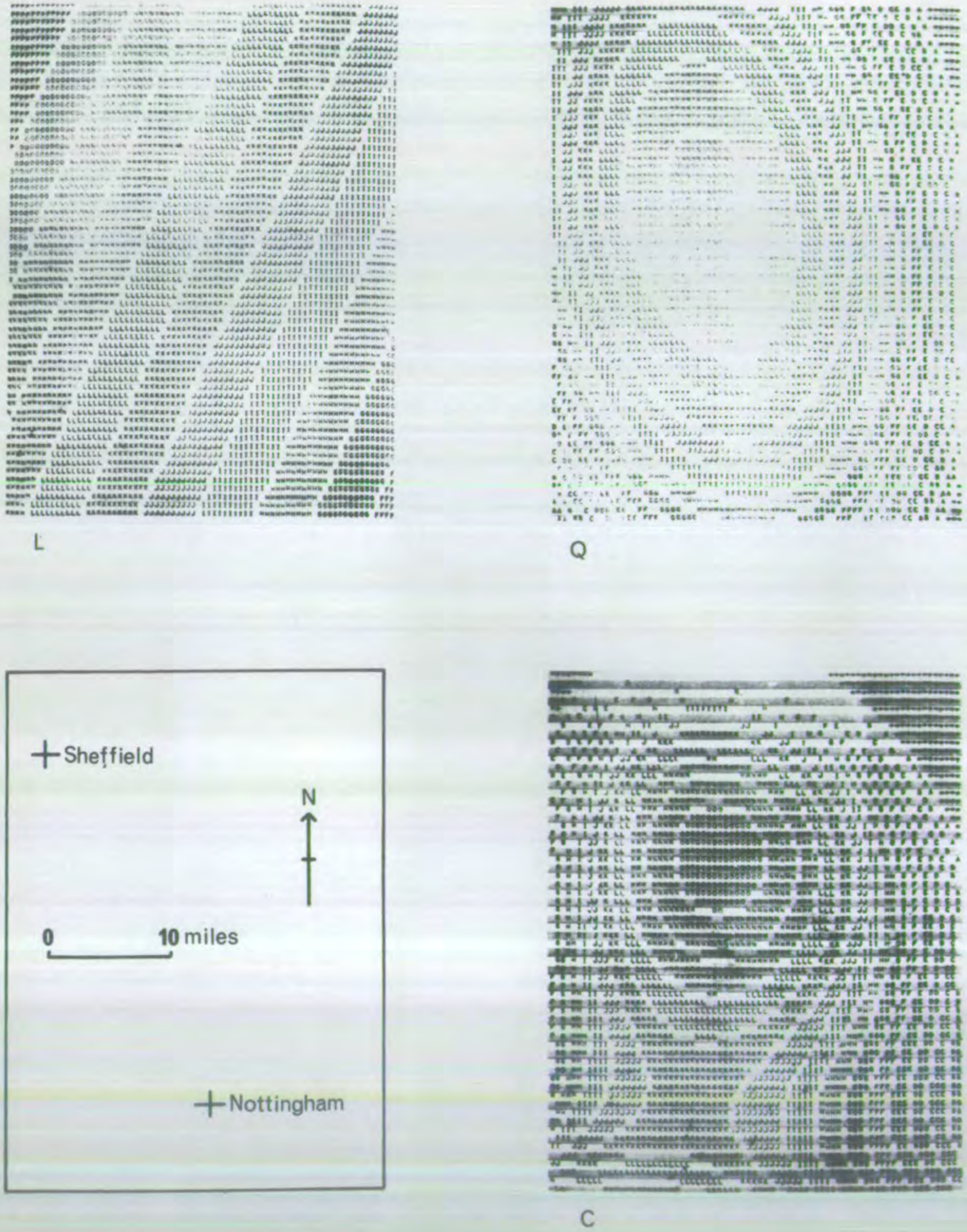
Si fixed sand/silt boundary

Sj fixed silt/mud boundary

Sx operator's estimate of Sj

Tij thickness of silt bed

Tix operator's estimate of Tij

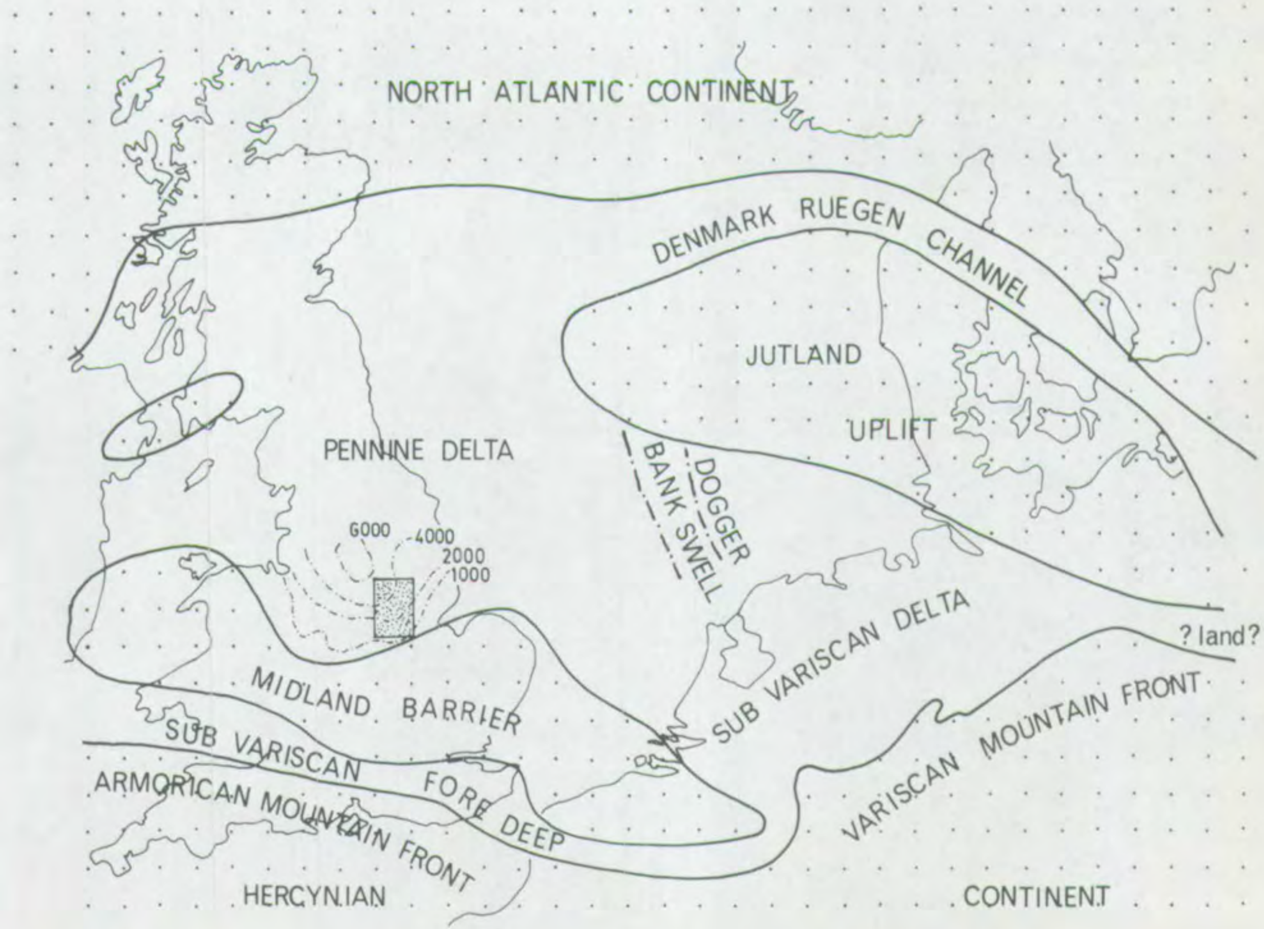


Figure(3.0.1) Linear (L), quadratic (Q) and cubic (C) trend surfaces of the subsidence necessary to emplace the section of strata under investigation.

PALAEOGEOGRAPHY

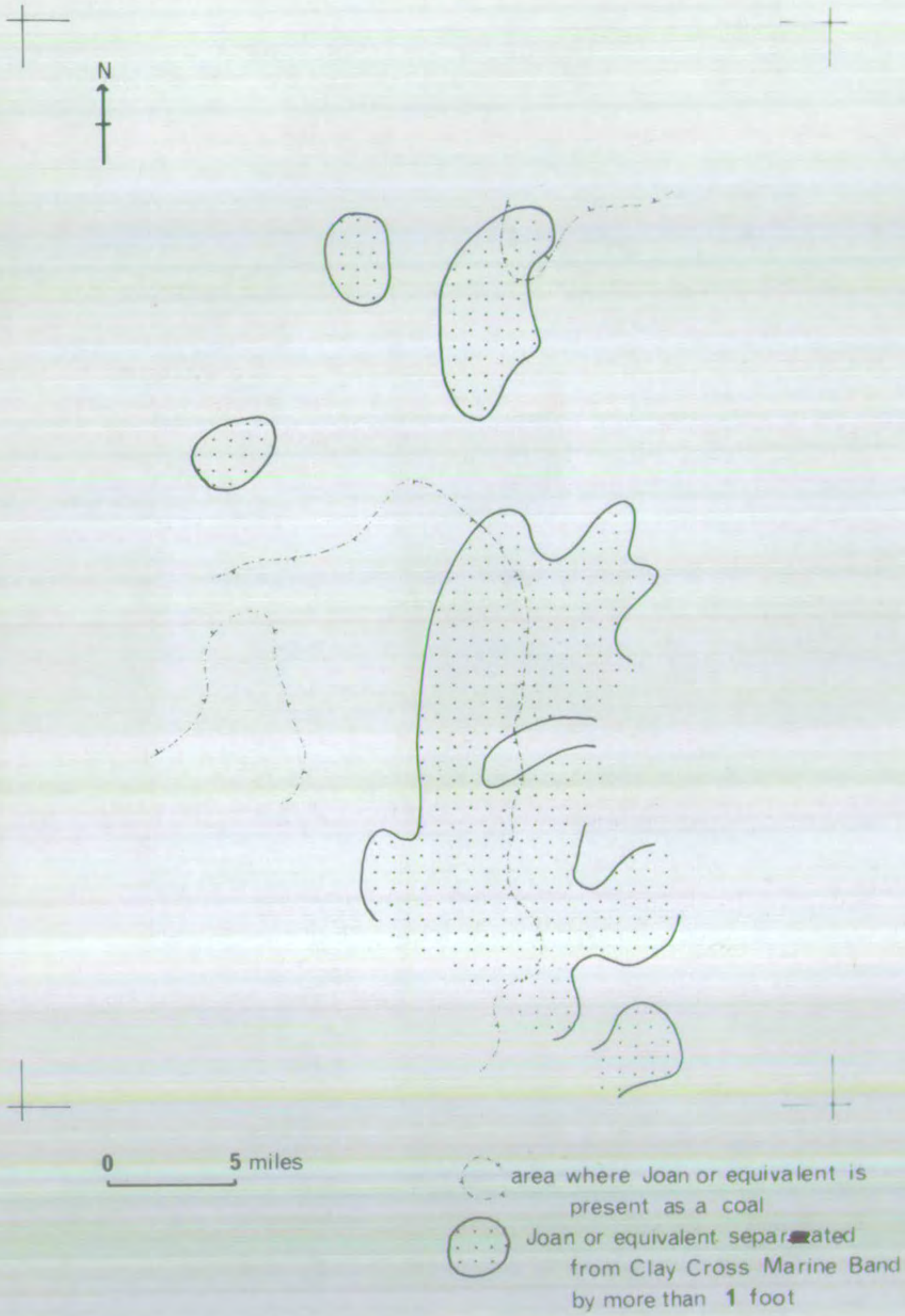
This short but important section is devoted to the reconstruction of the palaeogeography of Central England during the Westphalian Stage of the Carboniferous System. The model presented is largely based upon previous work and its interpretive use, therefore, does not involve any circular arguments. A better scientific approach would be to reconstruct the palaeogeography from one set of data and to describe the sedimentary features from a second set, distributed over the same area. This could not be done in the present study because there was insufficient data available. The model described below was taken as a working hypothesis in the absence of any reasonable alternative, and found to be at least consistent, on subsequent application.

Figure (3.0.1) shows trend surfaces up to cubic order extracted from data describing the subsidence necessary to emplace the section of strata under investigation, after the effects of compaction have been removed. The linear surface increases progressively from the South-East to North-West, and therefore away from the Midland Barrier, figure (3.0.2), whereas the quadratic and cubic surfaces demonstrate that the zone of maximum subsidence is restricted to the map area. However, since this zone lies towards the North-West, all three surfaces have a similar pattern over the larger part of the map. The data set used in these computations was obtained from section (7).



---- 2000 isopachs total Grey Coal Measures, feet

Figure(3.0.2) Westphalian palaeogeography ; after Bartenstein(1968).


N
0
5 miles
area where Joan or equivalent is present as a coal
Joan or equivalent separated from Clay Cross Marine Band by more than 1 foot

Figure(3.0.3)

The strong positive correlation between the total thickness of the Modiolaris Zone and the number of cycles contained (Duff and Walton 1964) arises from the repeated distal splitting of coal seams (Elliott 1968) and suggests that subsidence and deposition were contemporaneous if not synchronous. The permanency of this characteristic throughout the Coal Measures implies that the average depositional dip did not vary greatly during the accumulation of the selected section.

It is necessary to be sure that the upper bounding surface of a unit was horizontal at the time of formation before the isopach simulation of the subsidence pattern can be accepted (Kay 1945). In this study the upper surface was taken as the base of the Clay Cross Marine Band, Anthracoceras vanderbeckei (Ludwig). The faunal distributions suggest that the marine acme coincided with the zone of maximum thickness of Coal Measures sediment. Calver (1968) concluded that during the accumulation of the marine band the water depth increased away from the Midland Barrier towards the North-West. If the transgression occurred across such a sloping shelf the base of the marine band was not horizontal at the time of formation and the isopach evidence must be set aside. Depth, however, is only one of a group of factors which can influence the distribution of invertebrate communities (see for example Craig and Jones 1966).

The base of the marine band closely overlies what is probably a continuous horizon of coal and seat-earth over most of the coalfield, including the extreme North-West and South-East as shown in figure (3.0.3). If, following Edmunds (1968), a transgressive dynamic model is proposed, where juxtaposed peat-forming and marine facies belts migrate up a sloping shelf, then the cycle below should thicken shorewards, since it must be regressive and is composed of non-marine sediments. As shown in figure (4.8.3), the cycle thickens away from the Midland Barrier and, therefore, away from the nearest shoreline. Apart from the improbable sequences generated by the dynamic model (Oomkens 1967), the stronger development of the Joan coal in the North-West, towards the centre of the Pennine Basin, suggests that the time available for peat accumulation was not diminished near the area of marine acme, where the switch from regression to transgression should occur.

The alternative static model, where the sea floods across a peat swamp covering the whole study area, involves the base of the marine band being everywhere at about the same level at one instant in time, if the usual topographic limitations on peat growth are accepted (see for example Williams et al 1968). The faunal variations may still be attributed to depth differences, if the suggestion is invoked that marine bands take much longer to accumulate than equal thicknesses of non-marine sediment (Tonks et al 1931), thus allowing basinwide downwarping to exceed sediment accumulation.

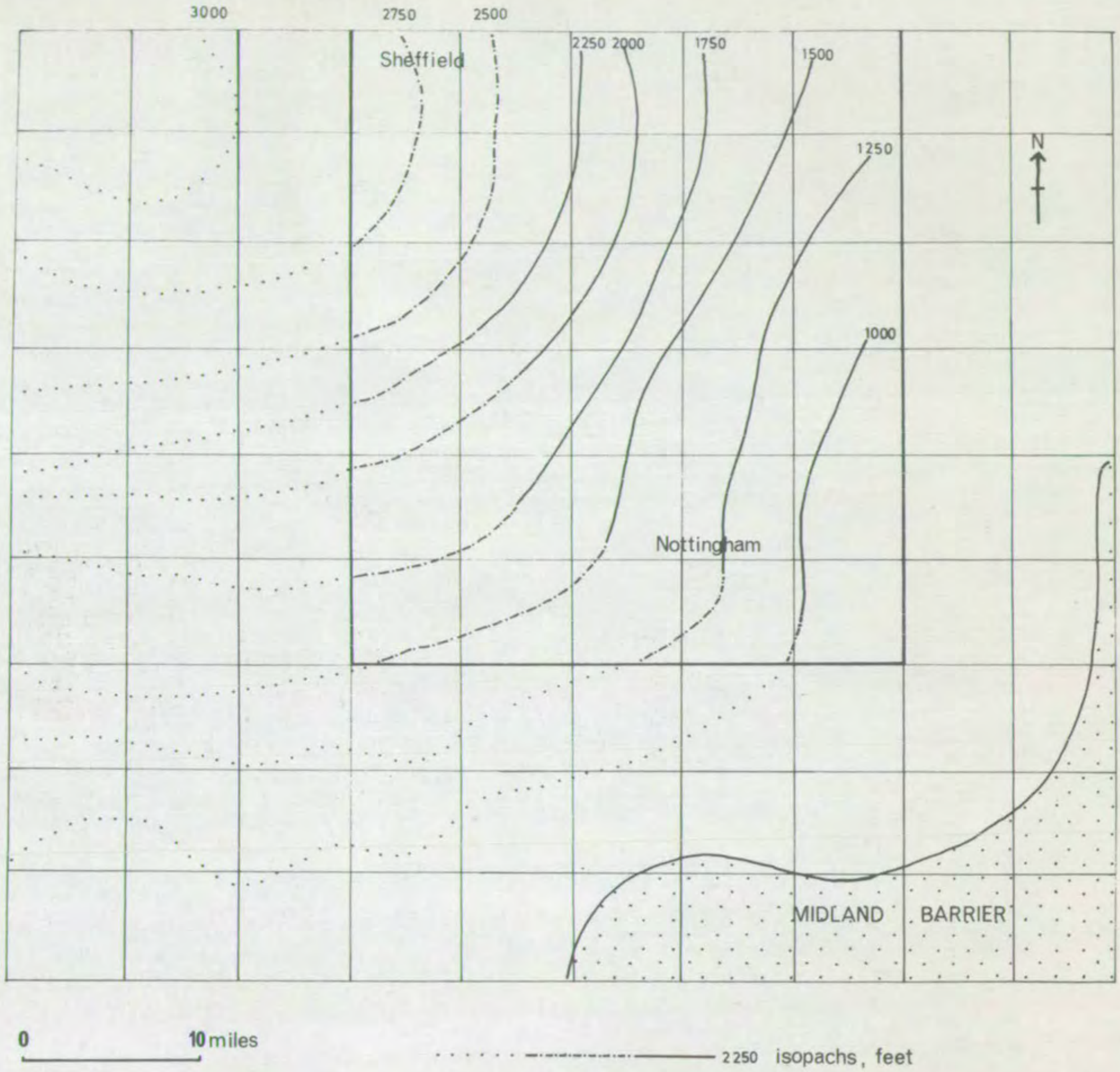
The apparent illogicality of proposing a depositional slope for sediments immediately beneath a coal and not for those above, does not invalidate the argument. The areal patterns of coal thickness, section (4), correspond to the contours of total subsidence, figure (7.4.2), suggesting that peat accumulation kept pace with basinwide downwarping, and therefore nullified its effect.

There is, therefore, some justification for accepting the linear trend surface as an approximation to contours on the average depositional slope. Wills' (1956) isopachs of his "palstage 1b", shown in figure (3.0.4), have been used subsequently in preference to the linear trend surface, to which they bear a reasonable similarity, for reasons of objectivity and accuracy, since they are based upon a much greater thickness of strata than the section under investigation. If the trend surface had been used, any interpretation based upon correspondence of component and sum of components (see section 5) would be biased by the closed number system involved.

From the linear trend surface it is possible to estimate the maximum possible depositional dip, which would arise in the basin necessary to contain the interval from the Threequarters coal to the Clay Cross Marine Band, in the unlikely event of it being deposited as a whole. The slope would be about 0.002% compared to the present 0.07% for the Gulf of Mexico. This result has some bearing upon later discussions of the depositional environment, since Wermund (1965) has suggested that slopes of this magnitude and greater can arise from local topographic variability.

3.1 Conclusion

The contours of Will's (1956) isopach map of his "palstage 1b" have been taken as an approximation to contours on the depositional slope, during the period of accumulation of the section of strata under investigation. The applicability of the contours of palstage 1b is verified by



Figure(3.0.4) Isopachs of "palstage 1b" in the Pennine Basin ; after Wills(1956).

their similarity to contours on trend surfaces of the total subsidence required to emplace the strata between the Threequarters Coal and the Clay Cross Marine Band. The simple model may be an oversimplification, since the depositional slope was probably so slight as to be masked by local topographic effects.

The Pennine Basin can probably be considered as a fairly simple depositional basin because subsidence, concurrent with sediment accumulation, increased progressively away from the nearest landmass.

section 4

STRATIGRAPHIC ANALYSIS

4.1 Introduction

The section of strata under investigation was not considered as a whole, because of the illogicality of using tendencies, established in this way, as a basis for the interpretation of variations in component parts of the same section. The use of the palaeogeography, discussed in section (3), does not extirpate the circular argument, but, since it is much more broadly based, minimises the possible error.

In the East Midlands Coal Measures, regional studies cannot be based upon sub-divisions at the level of an individual cycle because it is rarely possible to trace definitive horizons for large distances. The areal restriction of cycles arises because they are often bounded by coal seam splits and, less frequently, merge with their neighbours on the degeneration of intervening coals and seat-earths.

It was found that the section of the Coal Measures chosen for analysis could be divided into 7 'intervals', on the basis of the continuity of marker horizons across the study area. However, that any sandstone occurring anywhere between two marker horizons must be completely enclosed by them, was used as an additional definitive maxim. These rules were relaxed to allow for the washouts, on a very local scale, of marker horizons under thick sandstones.

As defined, many intervals contained numerous cycles in some areas. For the purposes of the following discussion the term 'cycle' refers only to a wedge of sediment bounded above and below by a coal or seatearth, without any overtones of a preferred sequence of beds within the wedge.

In section (2) it was shown that the variability of the silt/mud grain size boundary, arising from operator error, was significant in modern reports. The boundaries of the usual clastic sub-division, of finer grain sizes, into sand, silt and clay are, therefore, hazy. The scheme was simplified to include just two categories, sand and clay. The former consists predominantly of sand but silt and clay may be interbedded, and the latter of clay possibly containing beds of silt and even fine sand. Mixed facies, consisting of equal proportions of the components, were recorded as the individual beds, grouping coarse silt with sand and fine silt with clay.

In practice this scheme worked reasonably well for the purposes of mapping total and sandstone body thickness in subsurface. However, lithofacies analysis in any greater detail is precluded.

The correlation of coal seams, essential for this type of analysis, was based primarily on the work of the National Coal Board, East Midlands Division, with additions from the Memoirs of the Institute of Geological Sciences. Many correlations were the work of the author who must accept responsibility for their accuracy.

The seven intervals are described in detail below. The evidence obtained from this traditional analysis initiated the quantitative studies described in subsequent sections.

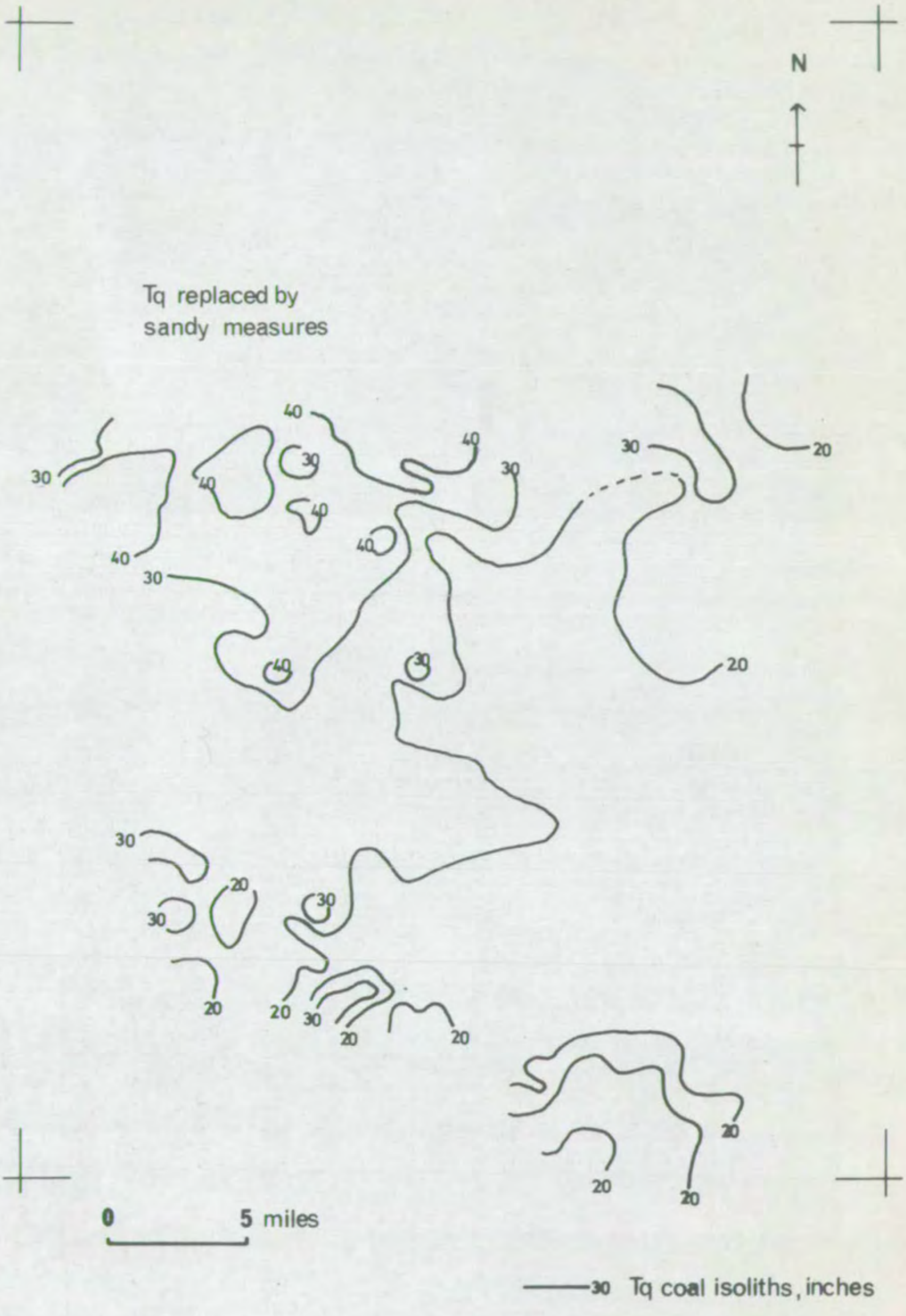
4.2 Threequarters to Low Main Coal, Interval 1

The interval is defined by the Threequarters and Low Main or Tupton coals. While the latter can be traced over the whole coalfield the former degenerates in the extreme North-West of the study area, where it is replaced by sandy measures associated with the top of the Silkstone Rock. The area of development of this interval is, therefore, slightly smaller than the study area.

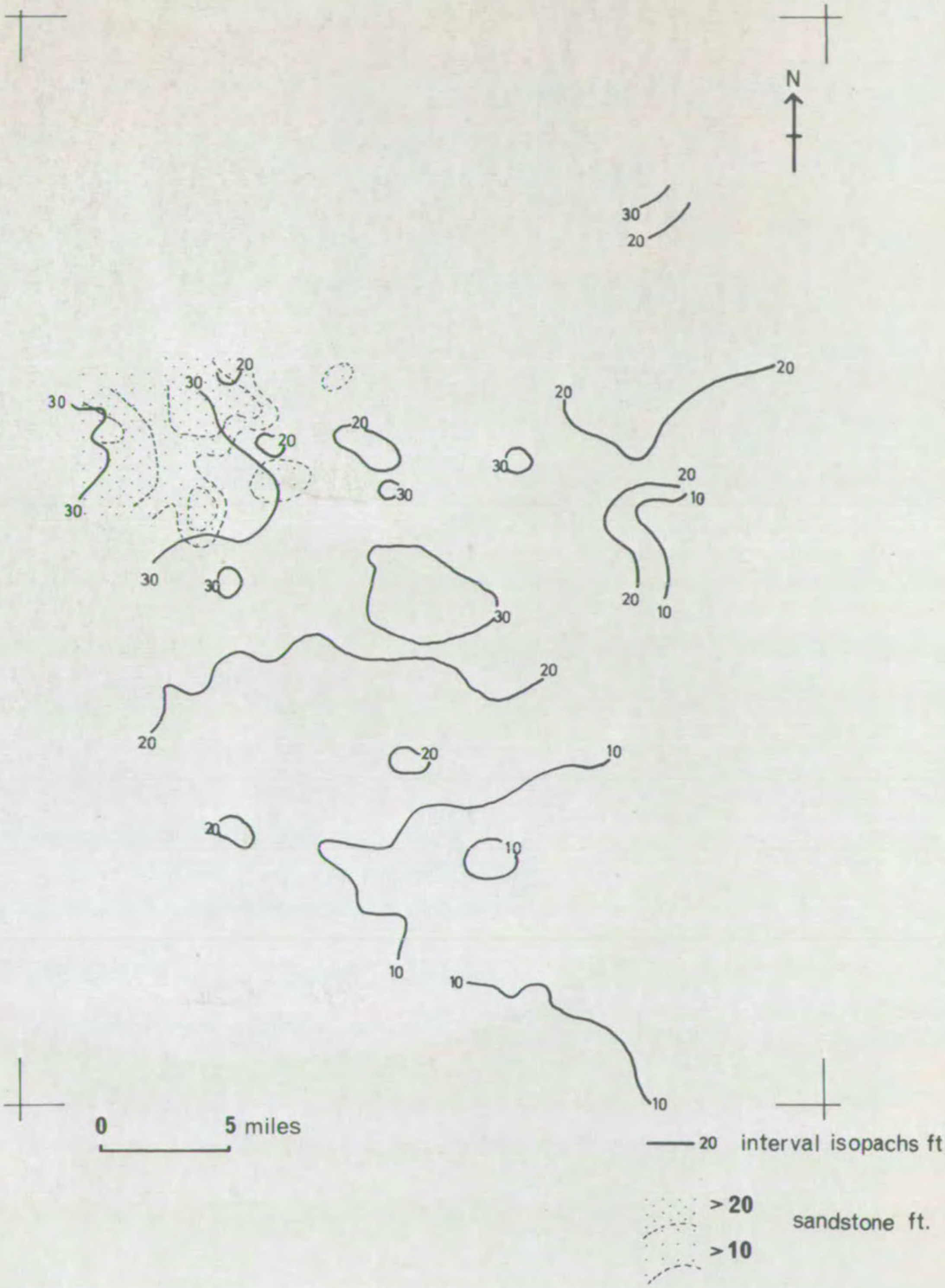
The interval consists of one cycle, neither of the boundary coals having a split which can be used for subdivision.

The gross thickness of the Threequarters coal, including dirt, is shown in figure (4.2.1). The pattern which emerges shows a progressive increase of thickness towards the North-West, and thus towards the centre of the Pennine Basin. This observation is important in that it refers to a single seam, suggesting that the similar trend for cumulative coal thickness, discussed as peat in section (7), does not arise from the introduction of new intermediate seams.

The thickness of the interval also increases steadily towards the North-West, figure (4.2.2), where the only sandstones are located, figure (4.2.2). The sandstones occur as unconnected pods. However, their restriction, apparently to the central parts of the Pennine Basin, may not be significant, since, for example, the map may only show part of a much larger discharge system.



Figure(4.2.1) Gross thickness of the Threequaters (Tq) coal, including dirt.



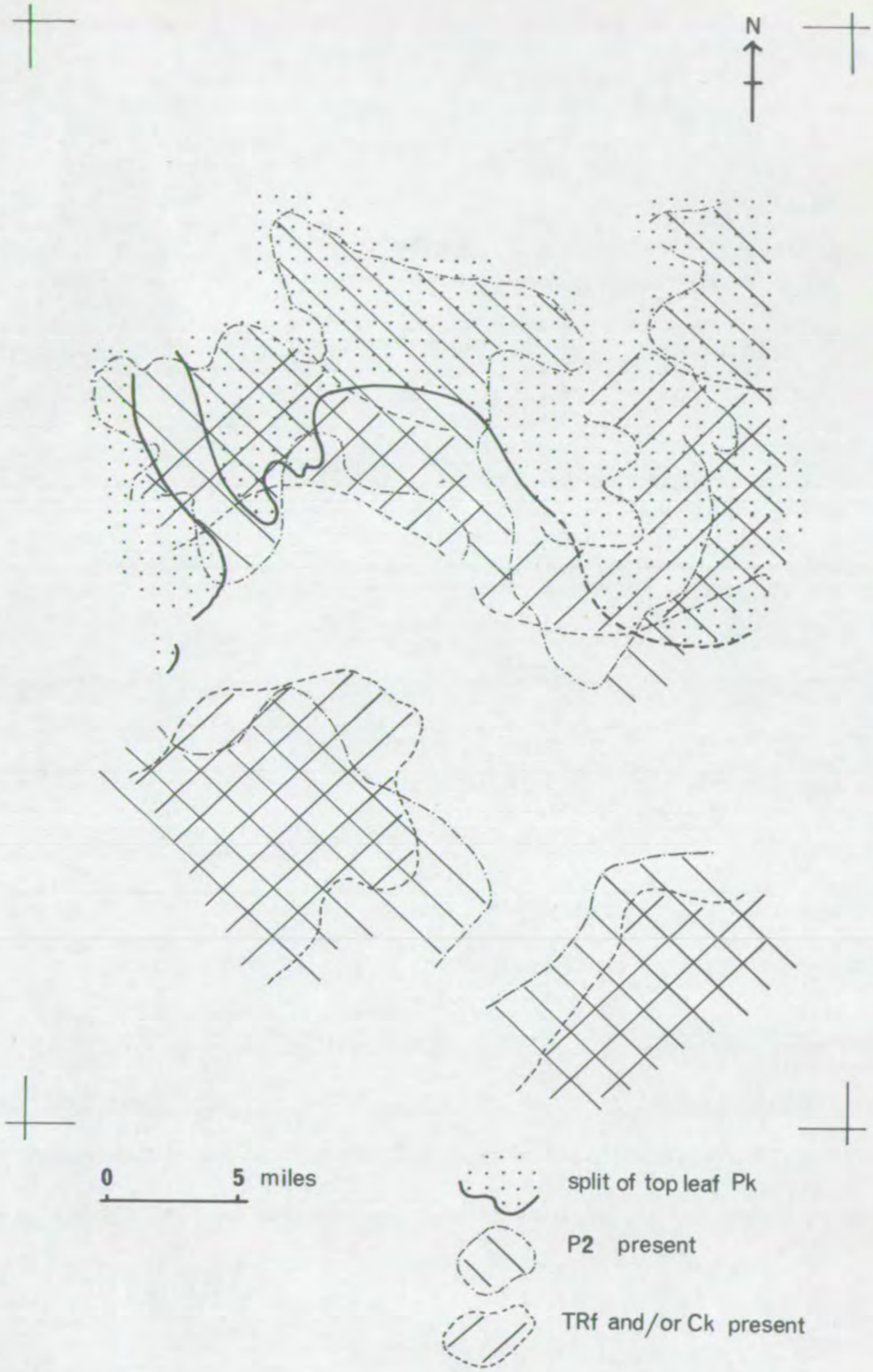
Figure(4.2.2) Total thickness of interval 1 and total sandstone thickness.

4.3 Low Main to Parkgate Coal, Interval 2

The definitive Low Main or Tupton and Parkgate or Piper coals occur singly or in recognisable combination over the whole map. The datum at the top of the Parkgate coal is in error by a few feet in the North because of a split, figure (4.3.1).

The Tupton coal can be separated from the Parkgate coal by up to three intermediate coals and seatearths, called the Second Piper, Tupton Roof and Cockleshell. Other, even more ephemeral, intermediates occur but have been left out of the analysis. Where present, the major intermediates divide the interval into two or three only, because it is almost impossible to map the Tupton Roof and Cockleshell as separate coals. Figure (4.3.1) illustrates the complexities which arise from subdivisions, and shows how the interval consists of one cycle in the centre of the map area where the sediments are very sandy. This feature is brought out in table (4.3.2), based on deviations from expected frequencies in a normal contingency table, which shows the trend of increasing complexity with thickness to be reversed where the interval is thickest. This dichotomy presents extraordinary correlation problems because of the loss of intermediate detail. Many of the conclusions are, therefore, based upon a few critical marginal records so that correct correlation is vital.

The top of the Cockleshell coal has been shown to be equivalent to the top of the Thorncliffe coal (which is primarily developed in Yorkshire) by Eden <u>et al</u> (1957). The base of the Tupton correlates with



Figure(4.3.1) Complexity map for interval 2.

	0	25	50	75	100	150	* feet
1	-0.43	+2.25	-1.57	-9.03	+1.85	+6.02	1 cycle
2	-0.50	+1.79	+0.68	-3.72	-3.13	-2.01	2 cycles
3	-0.61	-2.27	-3.24	+14.07	-4.51	-3.14	3 cycles
4+	-0.26	-1.80	-1.56	-1.31	+5.80	-0.86	4 and more cycles

Table(4.3.2)

Table(4.3.2) To show that the trend of increasing number of cycles with total thickness of interval 2* is reversed for maximum thicknesses. Values quoted are the difference between observed and expected frequencies.

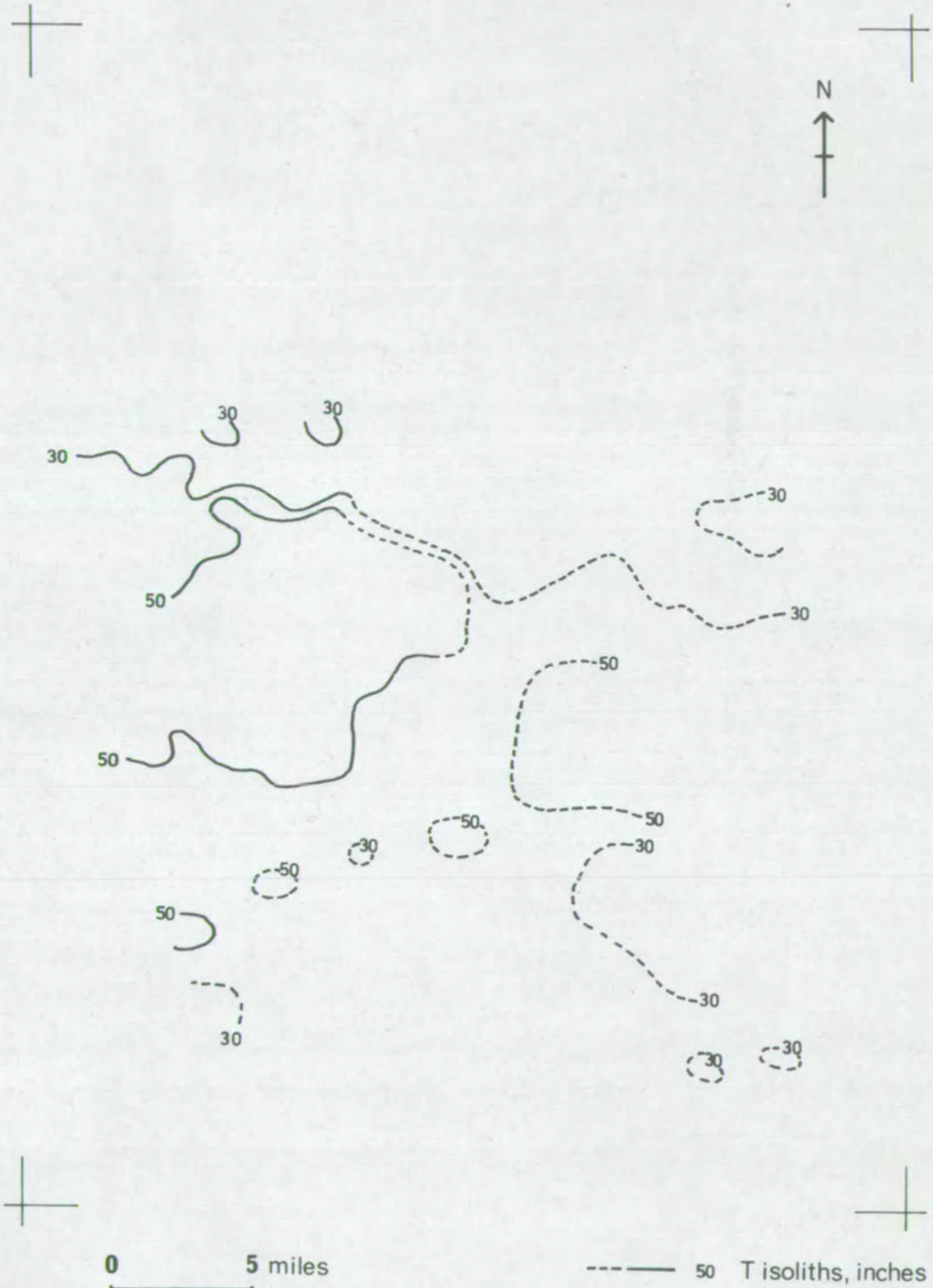
the base of the Thorncliffe where complete (e.g. 48201). The Tupton Roof coal is ephemeral and lies above the Cockleshell. Possible mis-identifications of the Tupton Roof as the Cockleshell, for example at 37211, 44313, and 63104, do not appear to affect the simplicity of the map of the thickness between the Tupton and Tupton Roof coals. The Cockleshell and Tupton Roof coals were, therefore, taken to represent a single horizon.

The Second Piper can be traced towards the central sandy zone, and the degeneration of coal and seatearth to seatearth alone prior to disappearance, suggests that it was not deposited over the whole area. The First Piper coal (known simply as the Piper where the Second Piper is absent) combines with the Second Piper in the extreme South-East, near the Midland Barrier, and in the North to form the Parkgate (e.g. 58303).

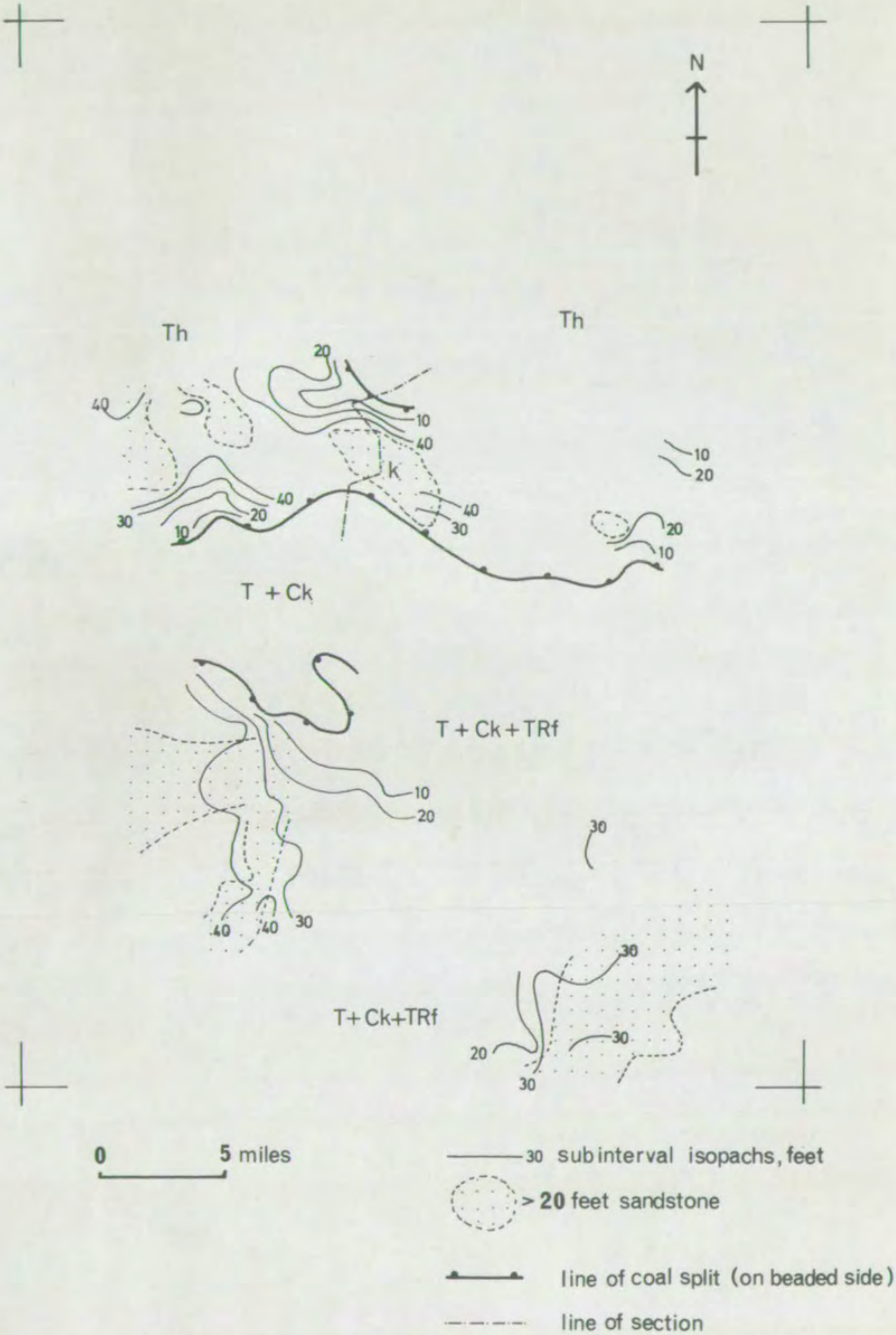
The gross thickness of the Tupton coal including dirt is shown, for its various combinations, in figure (4.3.3). The thickness pattern is clearly controlled by the Cockleshell split and there is no separate trend.

The lowest subinterval, defined by the Tupton Roof or Cockleshell coals, figure (4.3.4), is patchily developed. Areas of non-development are bounded by coal splits, everywhere except a small area where the Tupton Roof coal degenerates.

The northern prism of sediment corresponds to the thickest parts of interval 1. The southeastern and southwestern patches have no such coincidence. Sandstone in the South-East forms an elongate body which thins towards the Midland Barrier, but shows some tendency to thicken towards the North-West and may, therefore, be continuous with the major



Figure(4.3.3) Gross thickness of the Tupton (T) coal including dirt.



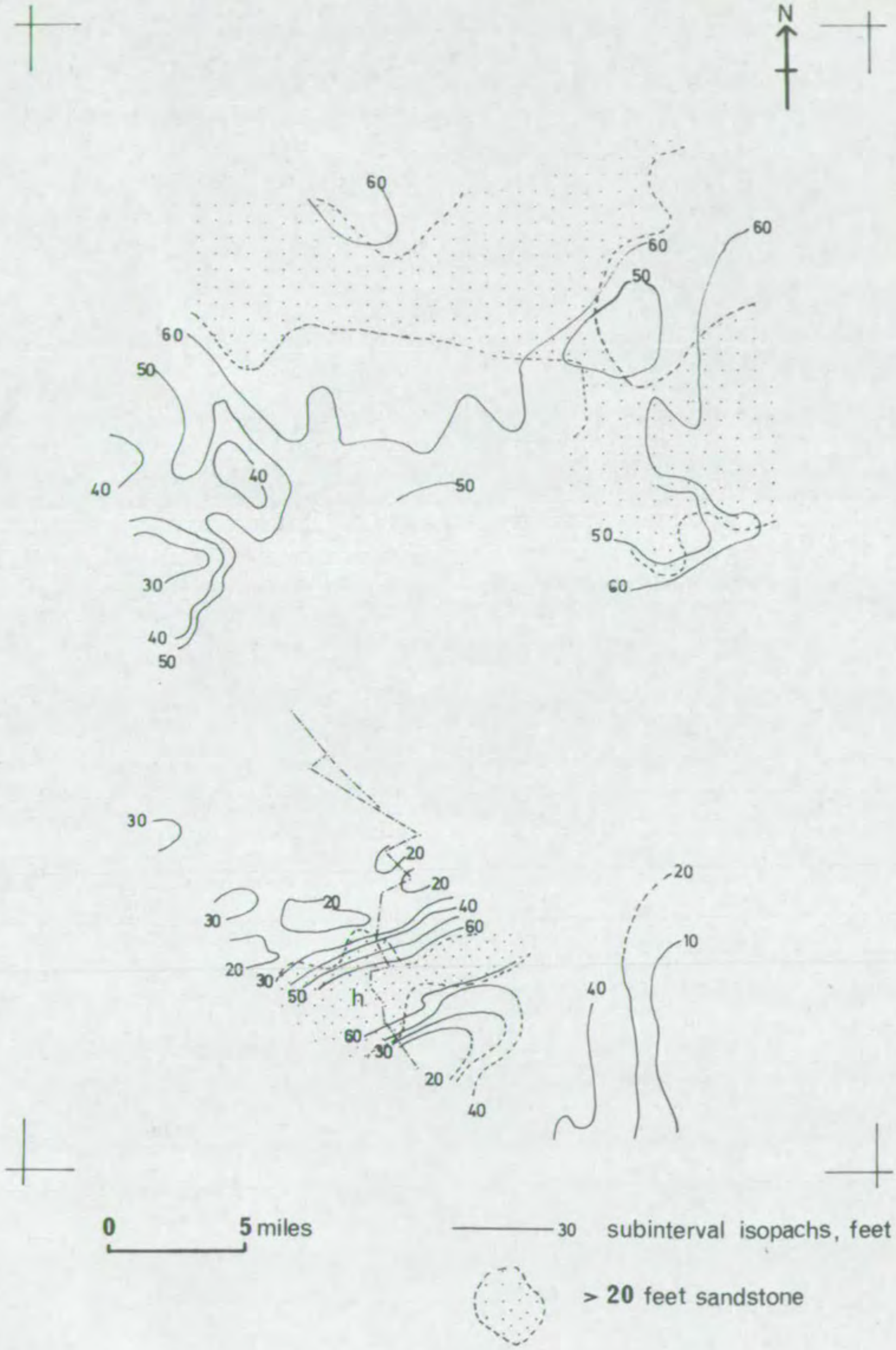
Figure(4.3.4) Lowest subinterval of interval 2 ; total and sandstone thickness.

central sandstone. In the South-West the sandstones thin towards the coal split and thus towards the North-East. The pattern shows two belts which coalesce in the direction of thinning. In the North the belt of development of this subinterval contains four disconnected pods of sandstone.

The patchy development of this subinterval could arise from either localised deposition or subsidence. The answer depends very much upon whether subsidence can control the distribution of sediment. This type of problem arises repeatedly in the studied intervals and is discussed further in section (6).

The middle subinterval is defined by either the Low Main, Cockleshell or Tupton Roof and the Second Piper coals. Figure (4.3.5) shows the distribution of sediment as far as can be traced. The degeneration of the Second Piper coal gives a false impression of patchy development. In fact, the only certain boundary is in the extreme South-East where the marginal coals combine.

The thickness of the subinterval in the North is variable but there is a definite increase in thickness southwards towards the area where the interval consists of one cycle containing a large sandstone body. The sandstones in this area form the only true sheet sandstone recorded. It may be significant that the sheet is restricted to the North, down the depositional slope, since Potter (1962) has suggested that similar bodies in the U.S.A. are formed during marine regressions. The southwestward extension, of the North-East area of the sheet sandstone, is lost through lack of control, but may be continuous with the central sandstone body because the subinterval, as a whole, thickens in

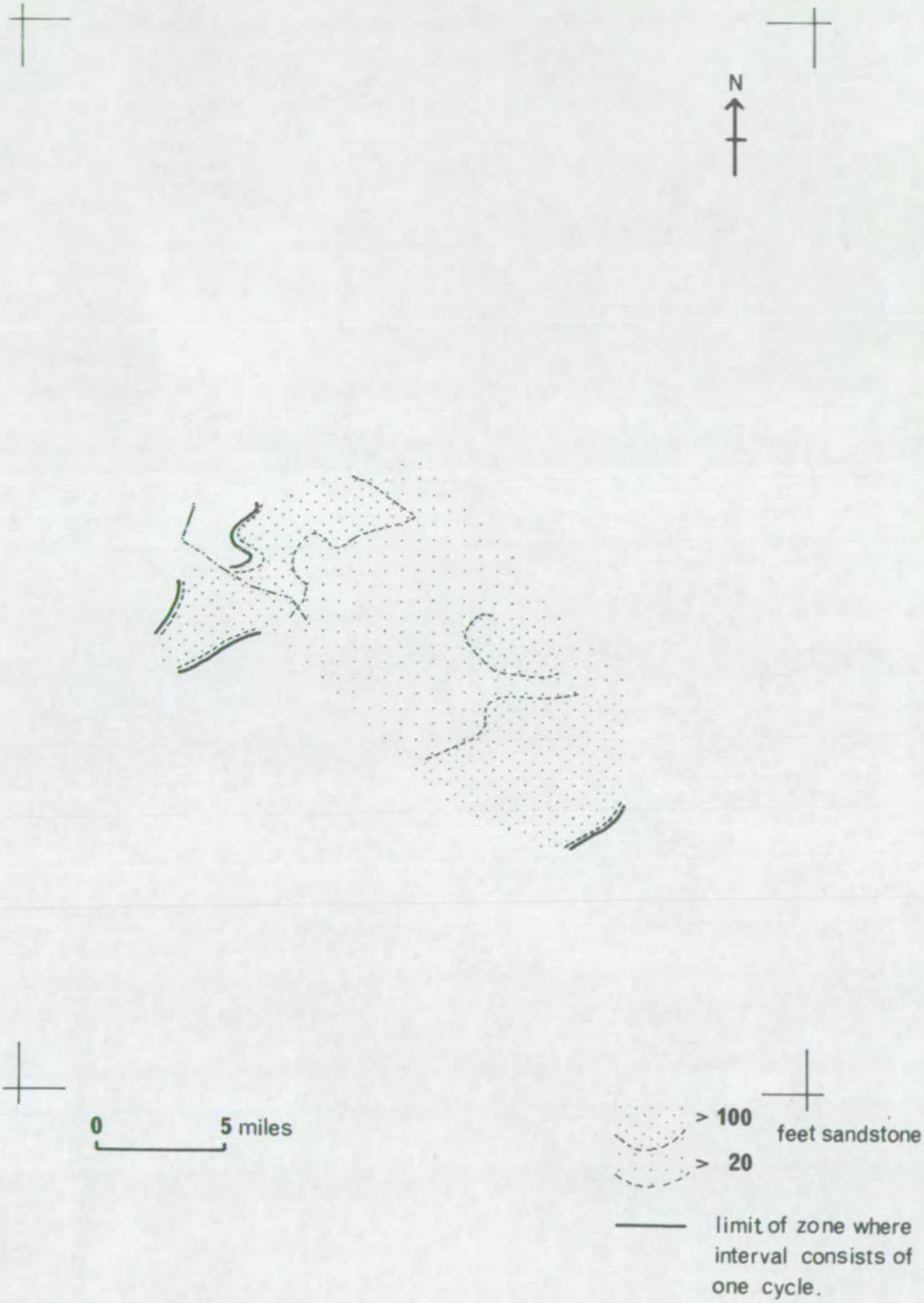


Figure(4.3.5) Middle subinterval of interval 2 ; total and sandstone thickness.

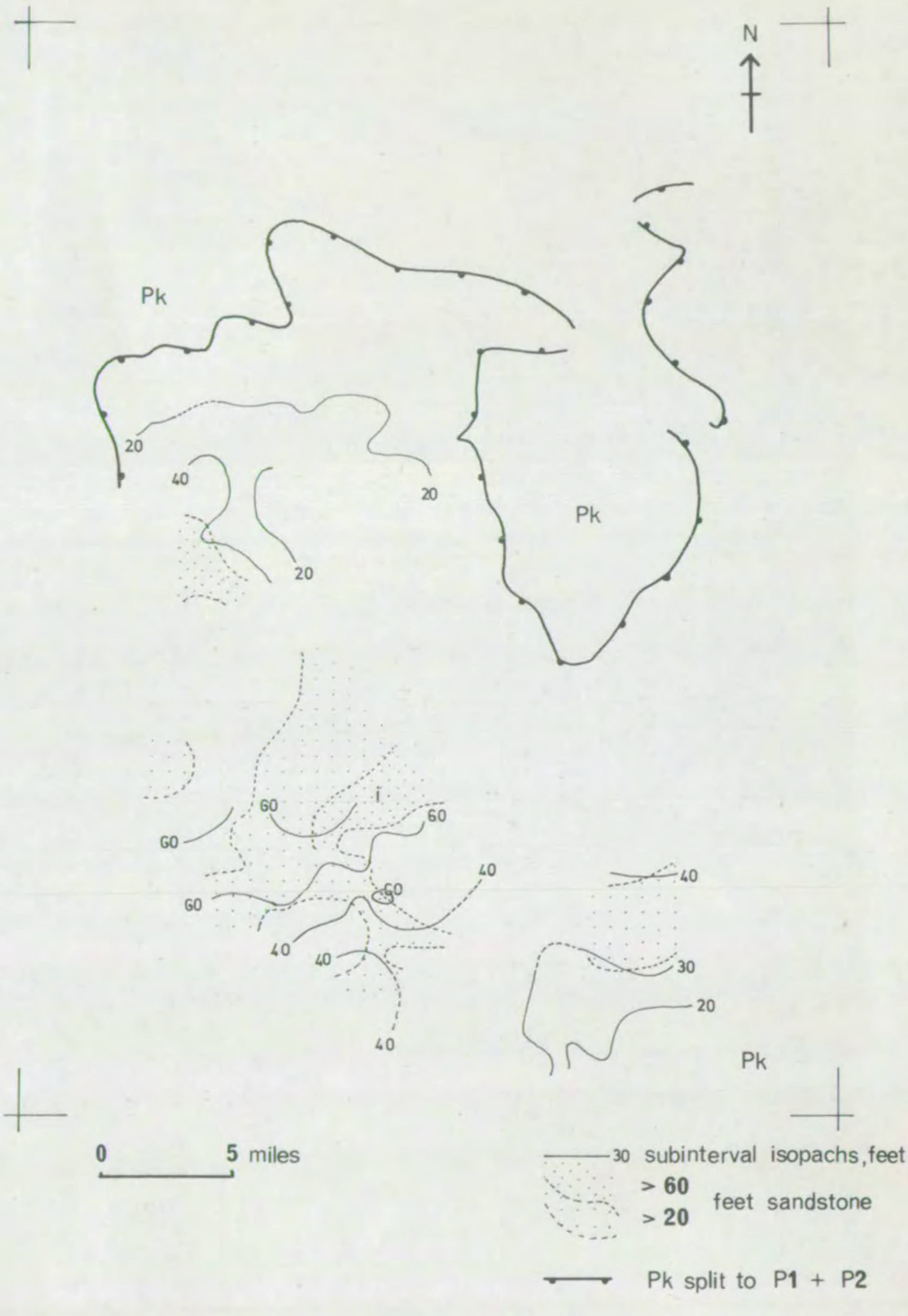
that direction. It should be noted, however, that for the most part the sheet consists of two leaves of sandstone separated by a thin coal and seatearth. If there is a simple genetic relationship between the sheet sandstone and the main central body, it must have been produced by some mechanism which could be maintained throughout the development of two cycles.

The sandstone body in the South-West forms a belt some 2 to 5 miles wide, at least 6 miles long and up to 120 feet thick. The belt axis trends towards the North-East and the body presumably connects with the main central sandstone. It is temptingly easy to interpret this relationship as an alluvial feeder and a basin of localised sand accumulation. However, as shown in figure (4.3.6), there is some evidence that this belt may continue its trend to the North-East, as suggested by the 100 feet sandstone isopach.

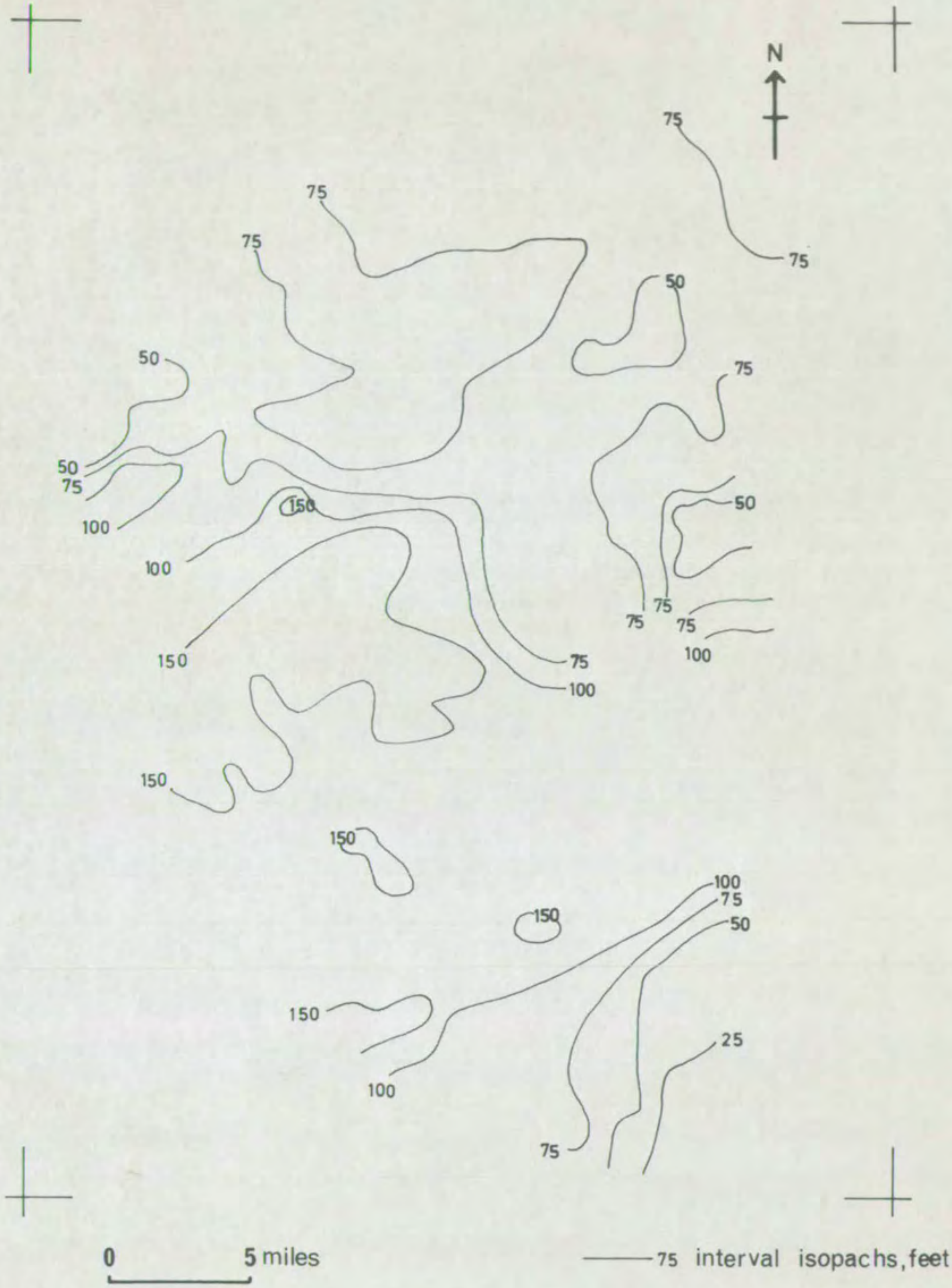
Comparison of this subinterval with the one below shows some examples of offset. The belt in the South-West lies neatly between the two southern sediment wedges of its predecessor, and the northern sheet is restricted to the North of the underlying belt. In addition, the central thick sandstone, which has its base in this subinterval, is distributed in such a way as to avoid the patches of development of the lowest subinterval in the North and the South-West. The northern margin of this body is extremely abrupt, by Coal Measures standards. For example, the interval consists of 3 non-sandy subintervals at 46101 but within a mile it has changed to one cycle containing a 100-feet thick sandstone (46102, 46204, 46306). This abrupt margin belongs to a belt of increased



Figure(4.3.6) Central area where interval 2 consists of one sandy cycle.



Figure(4.3.7) Top subinterval of interval 2 ; total and sandstone thickness.



Figure(4.3.8) Total thickness of interval 2.

sandstone thickness, greater than 100 feet, which like its southern counterpart trends towards the North-East, figure (4.3.6).

The third subinterval is defined by the First and Second Piper coals. The combination of these coals in the North overlies the area of development of the sheet sandstone of the middle subinterval. The subinterval is also bounded by the same split in the South-East, figure (4.3.7).

The sandstones are fairly widespread but contain two thick belts. One in the North-West, figure (4.3.7), trends South-East for a known distance of less than about two miles, and may form an extension of the central sandstone body. The belt in the South-West trends towards the North-East and is, therefore, parallel to, but offset from, its predecessor. There is a general tendency to thicken northeastwards into the central sandstone.

The total thickness of this complex interval, figure (4.3.8), increases towards the North-West from the extreme South-East. The simple pattern, reflecting Wills' (1956) isopachs for the whole Pennine Basin, is broken up in the centre of the map area by the interplay of the various sandstones. The zone of maximum thickness falls within the map area.

4.4 Parkgate to Deep Hard Coal, Interval 3

The interval is defined by the Parkgate, Piper or First Piper coal and the Deep Hard coal, everywhere South of the line marking the split of the top Parkgate leaf. The interval is not readily divisible but the sandstones were formed by three separate depositional events, which are marked off by thin coals and seatearths.

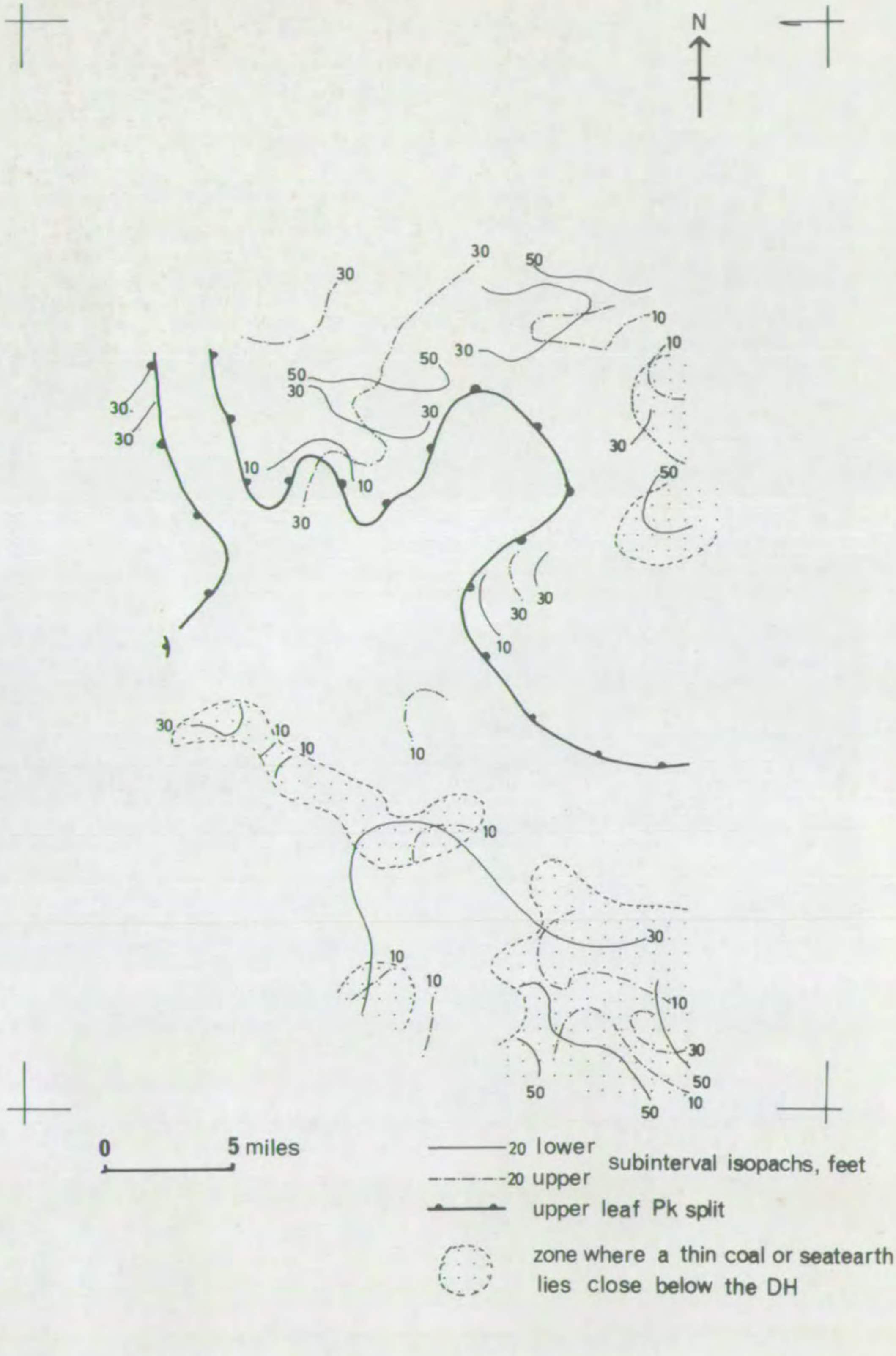
The lowest subinterval is defined by the Parkgate split, shown in figure (4.4.1), and the highest, stratigraphically, by the Deep Hard and an ephemeral group of thin coals and seatearths. The middle subinterval is defined by the upper and lower boundaries of the lower and upper subintervals respectively. Over much of the area the interval consists of one cycle, probably because the intermediate horizons degenerate, figure (4.4.1).

In the extreme North-West the Deep Hard coal becomes degenerate and few complete records are available. The area of deterioration coincides with that of the thickest parts of the Parkgate Rock.

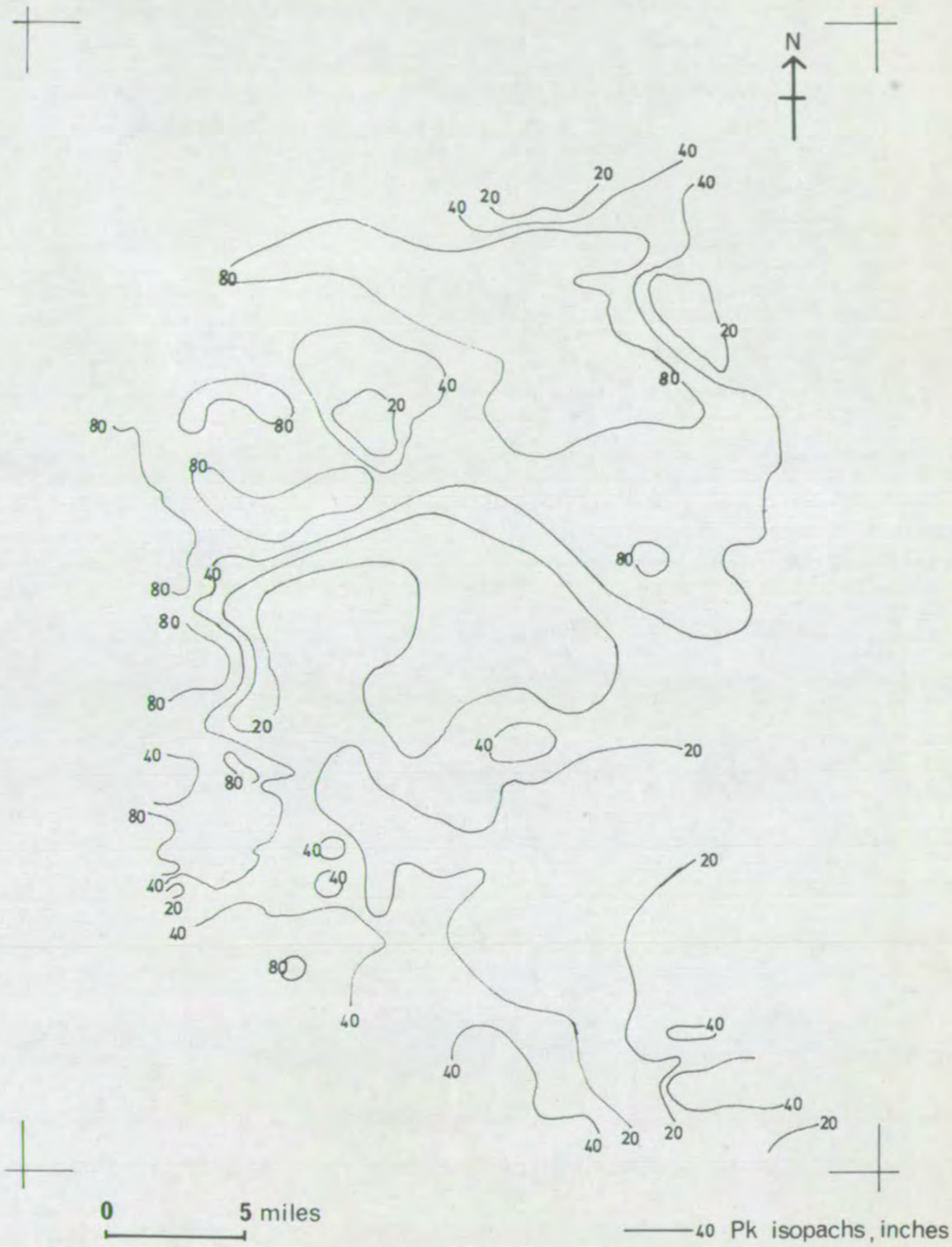
The gross thickness of the Parkgate coal, figure (4.4.2), does not appear to be affected in any way by the loss of the top leaf. The coal is thickest in the North-West but thinning towards the South-East is disturbed in the centre of the map area, where the coal is much thinner than expected. Although there is no precise correspondence, the coincidence with the thickest parts of interval 2 is notable.

The total thickness (figure 4.4.3), is also reduced to a minimum in this central zone. There is evidence of inverse proportionality between the thicknesses of intervals 2 and 3, on the small scale, in the eastern parts of the central area.

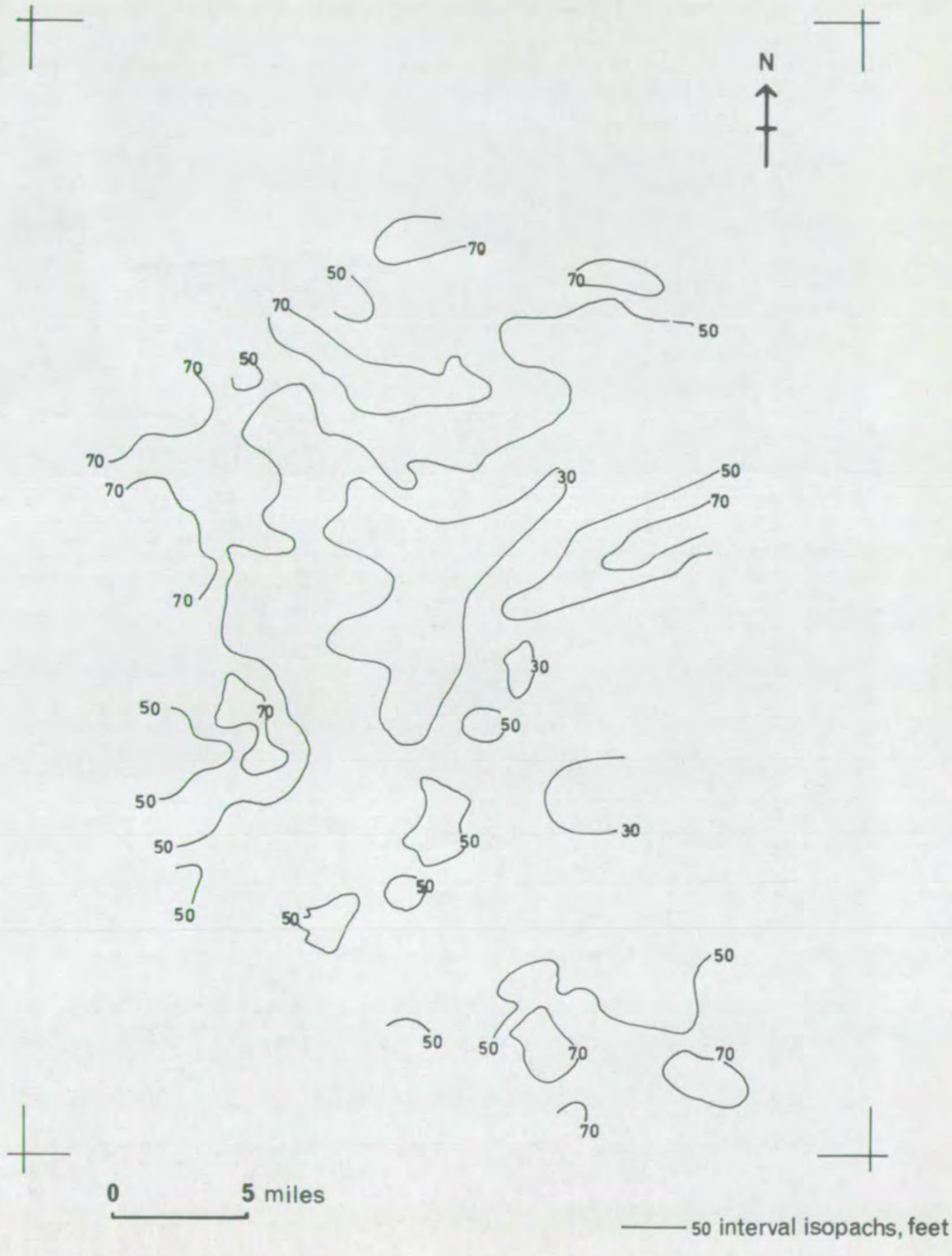
The main sandstone belt of the interval is probably restricted to the lowest subinterval. The isopachs of sandstone thickness, figure (4.4.4), could only be partly constructed from the available data and were completed using additional information from Mitchell <u>et al</u> (1947). The



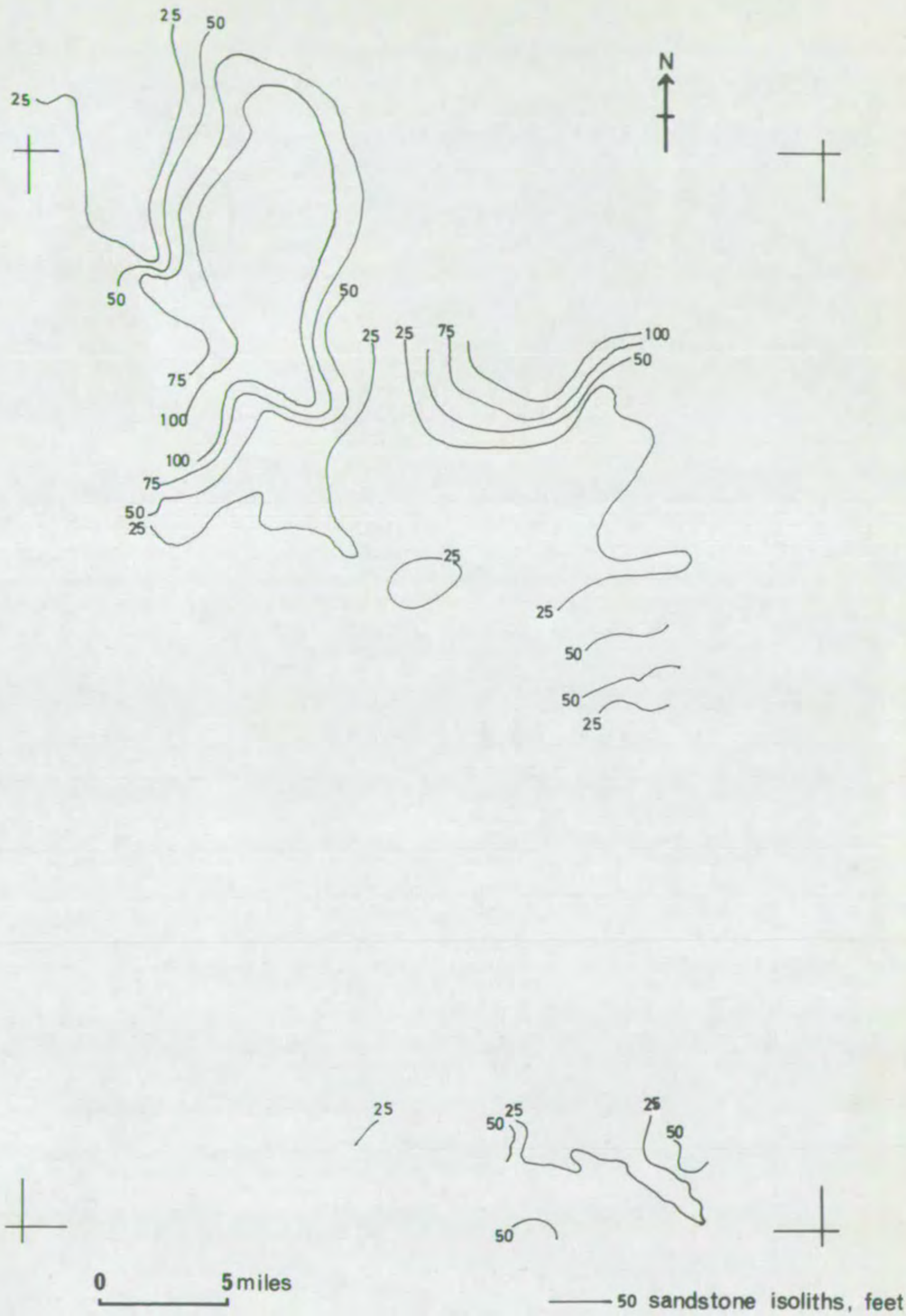
Figure(4.4.1) Composition of interval 3.



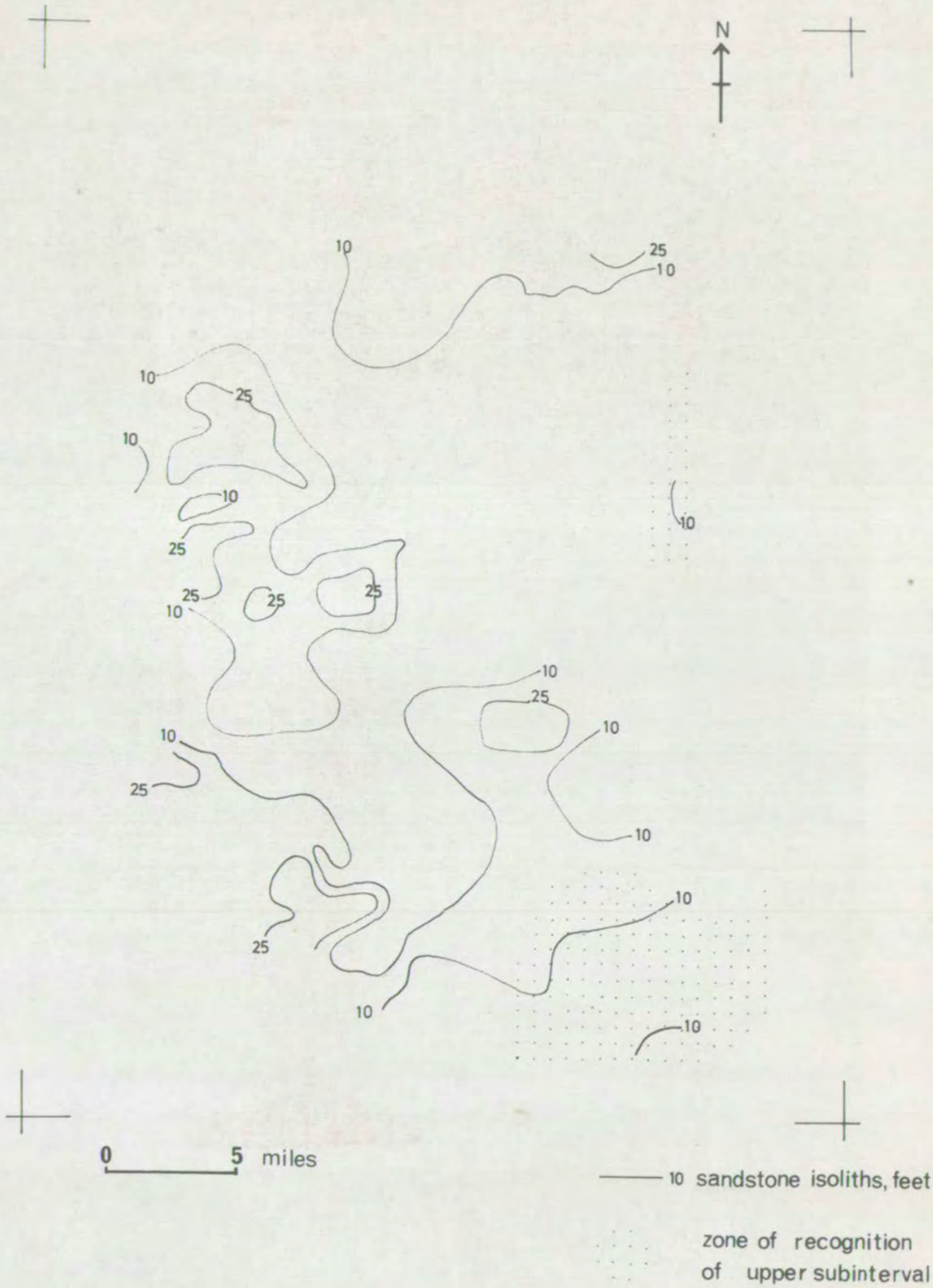
Figure(4.4.2) Gross thickness of Parkgate coal (Pk), including dirt.



Figure(4.4.3) Total thickness of interval 3.



Figure(4.4.4) Thickness of sandstone in the lower parts of interval 3.



Figure(4.4.5) Thickness of sandstone in the upper parts of interval 3.

sandstone body trends towards the North-North-East but is probably not continuous in this direction and, therefore, forms an elongate pod. It is 10 miles wide between the 20-feet isopachs but only 2 or 3 miles between the 75-feet isopachs. The maximum observed length is about 20 miles but the outcrop in the South-West precludes a knowledge of its original length. The greatest recorded thickness is 141 feet.

Part of a second sandstone body can be seen in the North of figure (4.4.4) and a second more restricted belt in the South. The stratigraphic equivalence of these two bodies is uncertain because of the lack of intermediate detail. Sandstones of the middle subinterval can only be identified in the South-East. The tendency for these sandstone bodies to thin towards the North-West suggests that they are not connected with sandstones in the centre of the area, where the interval consists of one cycle. Sandstones in the upper subinterval can similarly only be recognised in the South-East, figure (4.4.5). The hypothesis, that the sandstones of the central area are equivalent to those of the upper subinterval, is upheld by the simple nature of the isolith map, figure (4.4.5). Local highs of total thickness tend to avoid pods of sand in the central area.

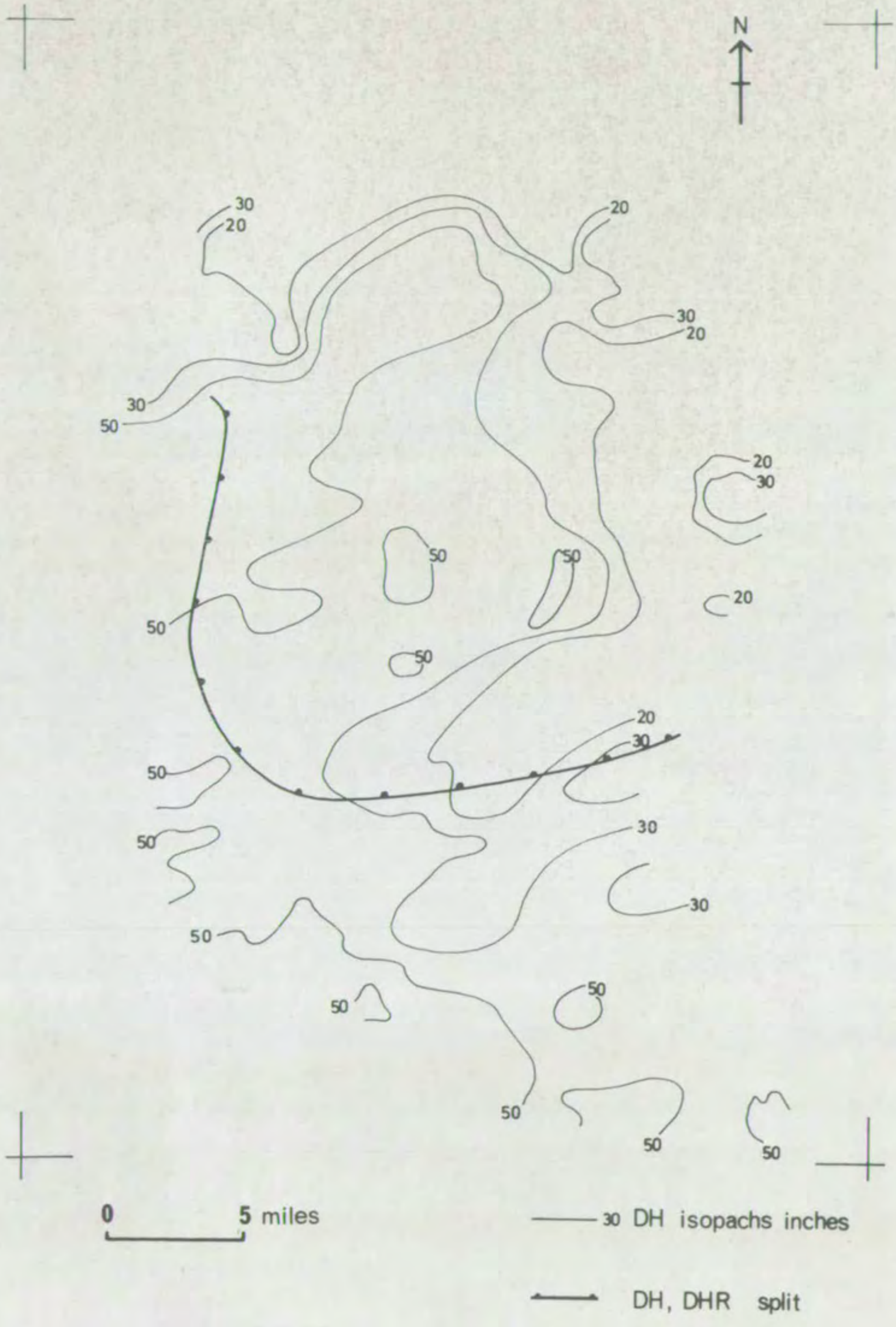
4.5 Deep Hard to Deep Soft Coal, Interval 4

The interval is defined by the Deep Hard and Deep Soft coals. The Deep Hard is recognisable everywhere except the extreme North-West, and splits only once to give a persistent rider in the North-East, figure (4.5.1). The Deep Soft coal, however, presents a number of difficult correlation problems. These involve the Roof Soft Coal and are, therefore, discussed in section (4.6).

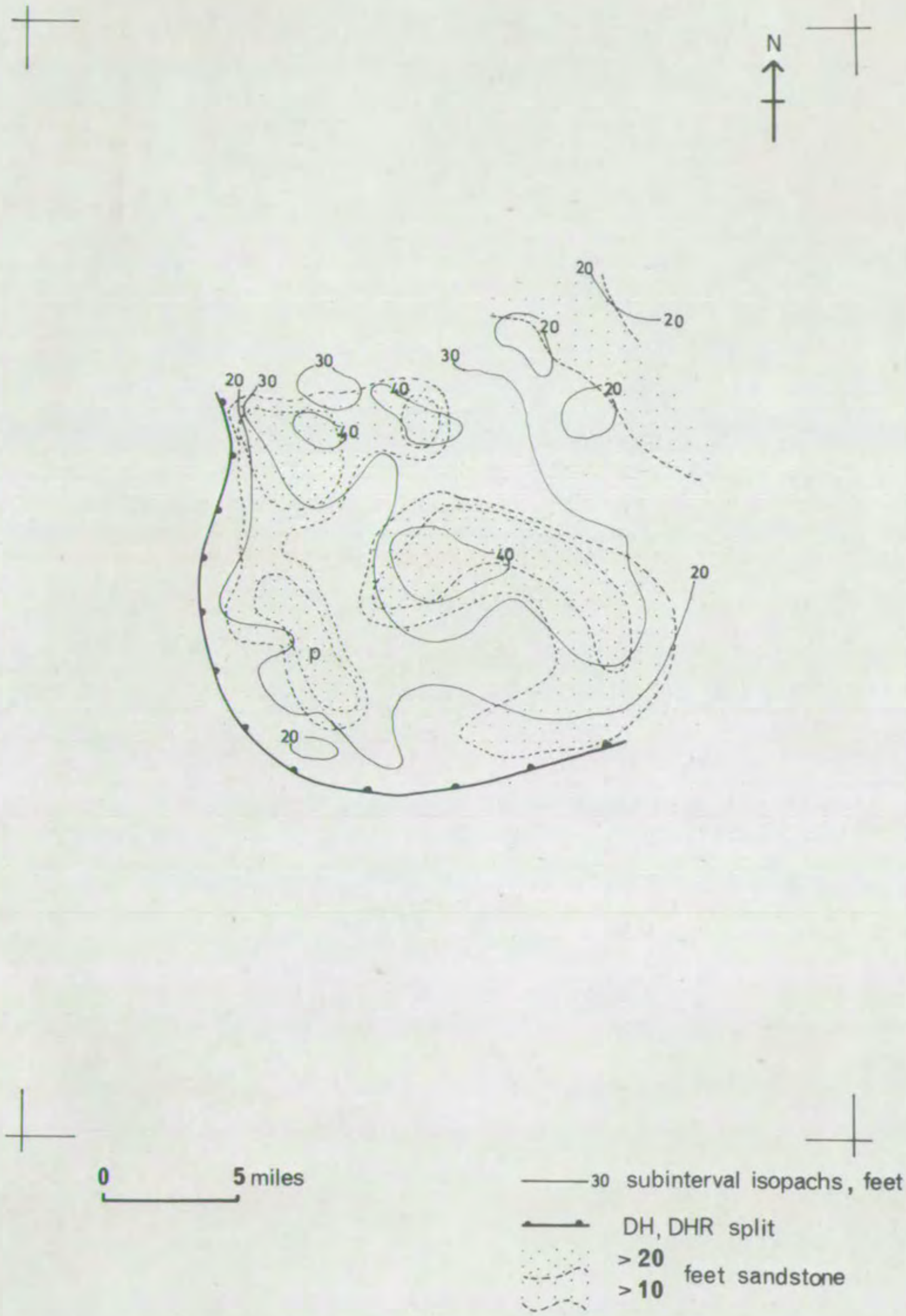
The split of the Deep Soft Floor coal from the Deep Soft and Deep Hard Rider from the Deep Hard give rise to a natural division into three subintervals. Over much of the area in the South the interval consists of a single cycle, contrasting with the North-West where 6 or more intermediate coals may be present.

The gross thickness of the Deep Hard coal, excluding of course the rider where split off, is shown in figure (4.5.1). Thinnest in the East, the coal thickens towards the North-West and South-West. Thickening towards the North is interrupted by thinning over an area coinciding with the main belts of the Parkgate Rock. The split of the Deep Hard Rider does not have any simple effect on the coal isopach pattern.

The progressively widening split of the Deep Hard coal and its rider reflects the thickness of the wedge of sediment of the lowest subinterval. Renewed thinning in the extreme East and North-East suggests that the subinterval may be enclosed by coal splits, figure (4.5.2). The sandstones, figure (4.5.2), are thin and restricted to a number of irregular pods, one of which thins along its northern margin suggesting that it peters out rather than joins the thick belt of sandstone shown in figure (4.5.3). However, the close proximity of boreholes 57103, where two moderately thick sandstones are separated by the Deep Hard Rider, and 57101, where the interval consists of one cycle with a thick sandstone,



Figure(4.5.1) Gross thickness of Deep Hard coal (DH), including dirt and Rider where combined.



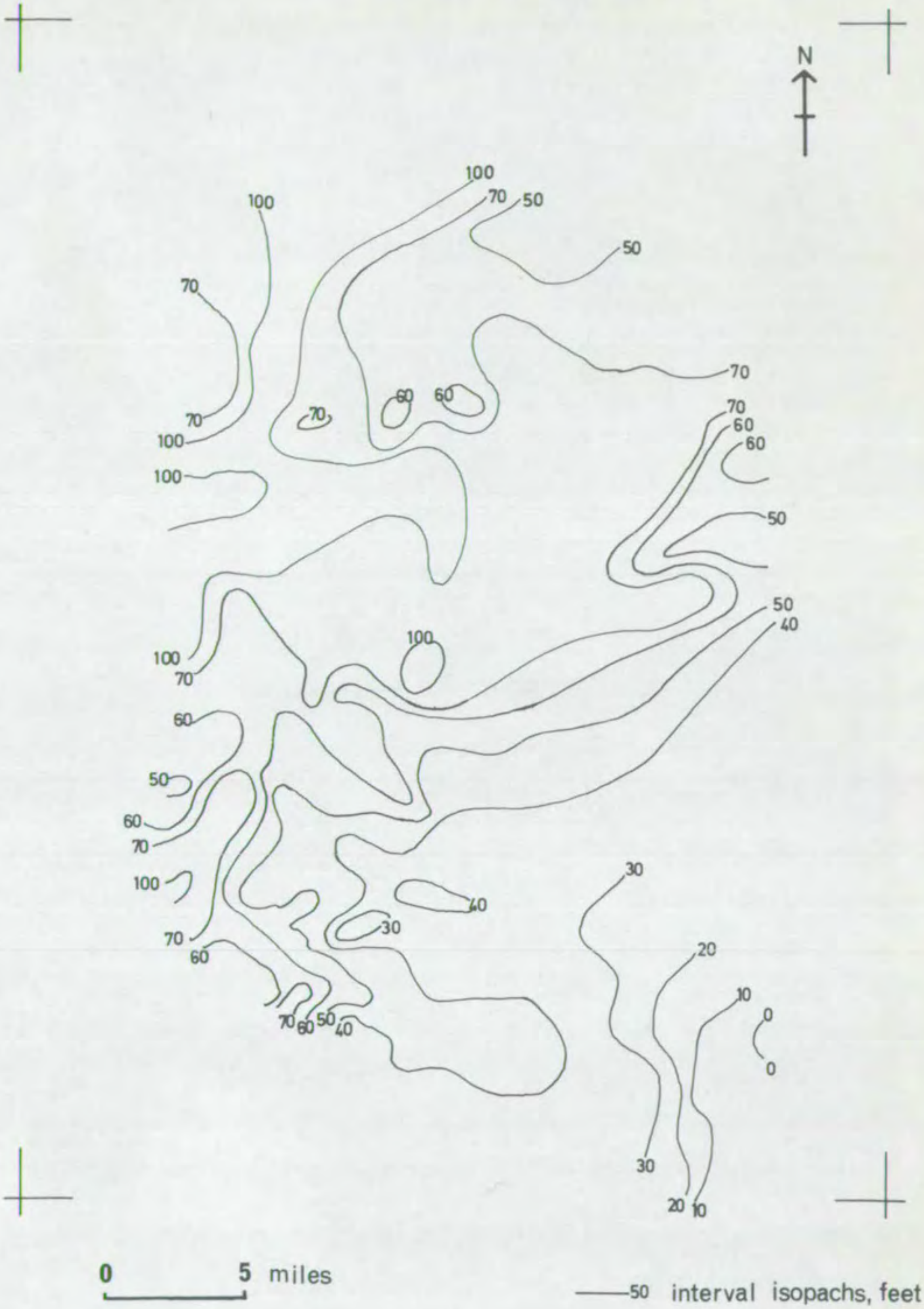
Figure(4.5.2) Lower subinterval of interval 4 ; total and sandstone thickness.

Figure(4.5.3) Thickness of sandstone above the Deep Hard Rider, in interval 4.

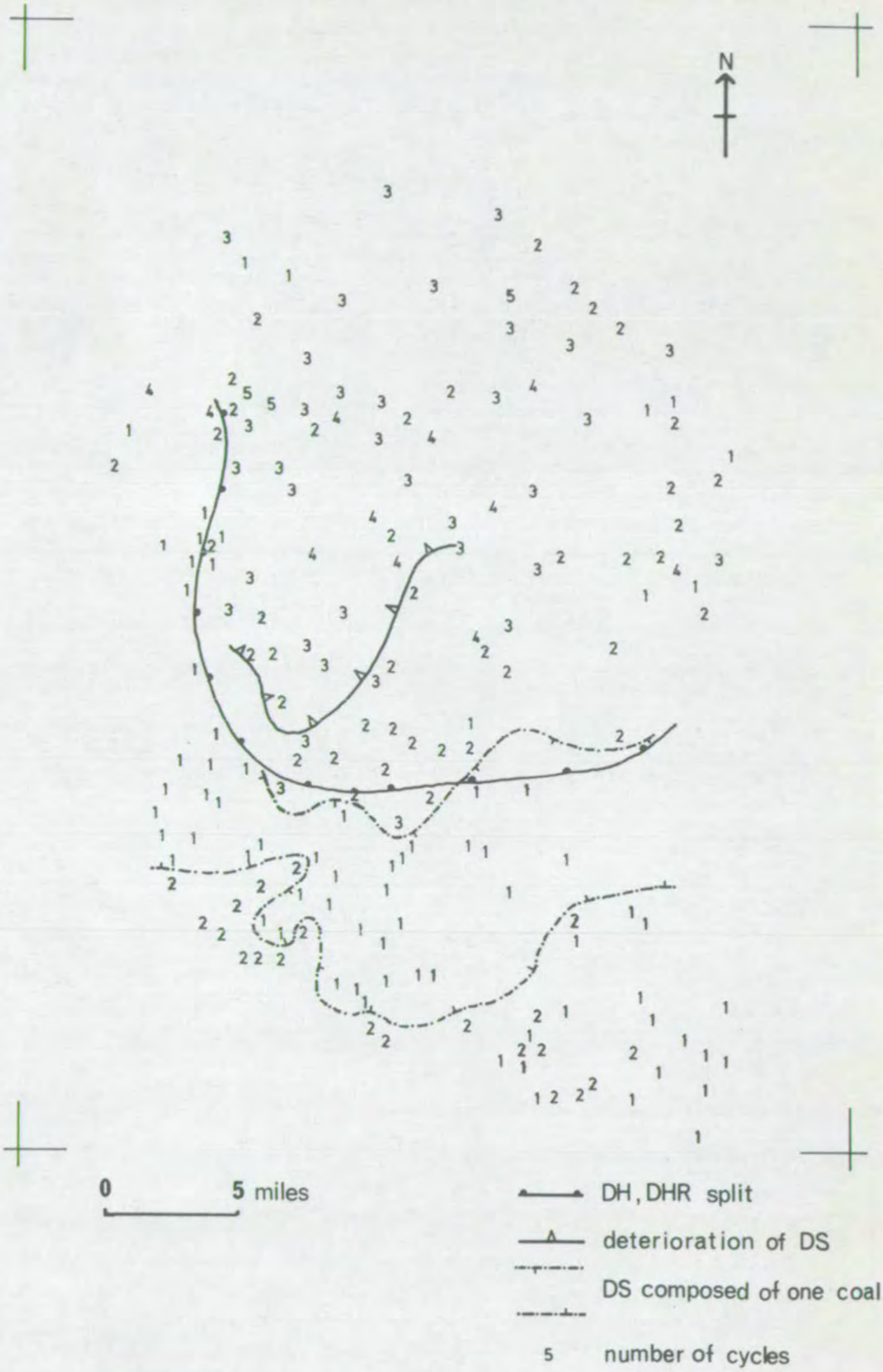
suggests that the subinterval may be stratigraphically equivalent to the lower parts of the Deep Hard Rock.

The middle subinterval, cf. figure (4.5.4), thickens progressively from the South-East to the West and North-West, where the pattern of isopachs is complicated by the presence of a thick sandstone. However, one of the thickest zones of development, in the South-West, contains no sandstone. In fact the sandstones of this subinterval are concentrated in the down-palaeoslope area, where they form two thick belts, one reaching 150 feet the other 80 feet, which coalesce towards the South-West. The belts tend to diverge, the southern trending East and the more northerly North-East, figure (4.5.3). The widths are extremely variable but 2, 3 and 4 miles are typical separations of 20-feet isopachs of sandstone thickness. The washouts, recorded on figure (4.5.3), parallel the belts but in fact are restricted to the lowest subinterval, and even avoid the thin sandstone pods. The washouts are, however, restricted to the West and not found anywhere else along the 25 miles that the belts can be traced in subsurface.

Eden et al (1957) stated that the Deep Soft coal is cut out by the upward extension of the Deep Hard Rock. While it is true that locally the Deep Soft coal may not have been deposited in some areas where the sandstone is thickest, the record of the Sitwell Thin at 46303 and its obvious equivalents, of a coal at 46302 and seatearths at 46304 and 46305, implies that the Deep Soft coal, like the Parkgate and Deep Hard coals, degenerates over a thick sandstone. Deterioration is partly accomplished by repeated splitting in the areas flanking the Deep Hard Rock, figure (4.5.5).



Figure(4.5.4) Total thickness of interval 4.



Figure(4.5.5) Areal distribution of the number of cycles in interval 4.

The main belts of the Deep Hard Rock are offset to the North from the sandstones of the lowest subinterval. However, if lateral continuity could be proved, this offset would arise naturally through the spreading of the environment, in which sand was being accumulated, over areas where intermediate coals were being formed. The offset of the Deep Hard Rock to the South of main belt of Parkgate Rock could not arise through co-deposition because they are almost ubiquitously separated by the Deep Hard Coal. However, the two sandstones form a multistory body in few places where the intervening coal has been washed out.

Figure (4.5.4) shows the interval thickness including the lowest subinterval. Like interval 3, thick zones in the South-West tend not to be sandy. The fairly simple pattern of increasing thickness towards the North-West is again complicated where the interval contains thick sandstones.

There appears to be little correspondence between total thickness of the interval and the number of cycles, figure (4.5.5). However, the splitting of the Deep Soft coal towards the Deep Hard Rock suggests that subsidence, over and above the regional, was proceeding below the sandstone bodies as more sediment was being added.

There appears to be no simple relationship between the thicknesses of intervals 3 and 4.

4.6 Deep Soft to Roof Soft Coals, Interval 5

It may not be justifiable to use the term 'interval' to describe this part of the succession, even though both requirements are fulfilled, because the Roof Soft coal forms an integral part of a group of seams known collectively as the Clay Cross Soft. However, this group can itself be regarded as an interval, so that number 5 can be defined as the section of strata between the Deep Soft coal and the base of interval 6. The Roof Soft coal can be traced over the whole area, whether alone or in combination with the Top Soft, forming the Sitwell, or Top Soft plus Chavery, forming the Flockton.

The Roof Soft coal shows a wide range of development. In the West and South-West it is commonly 2 to 3 feet thick but in the East and South-East it is represented by a thin cannel. In the West this cannel overlies an inferior coal or bat.

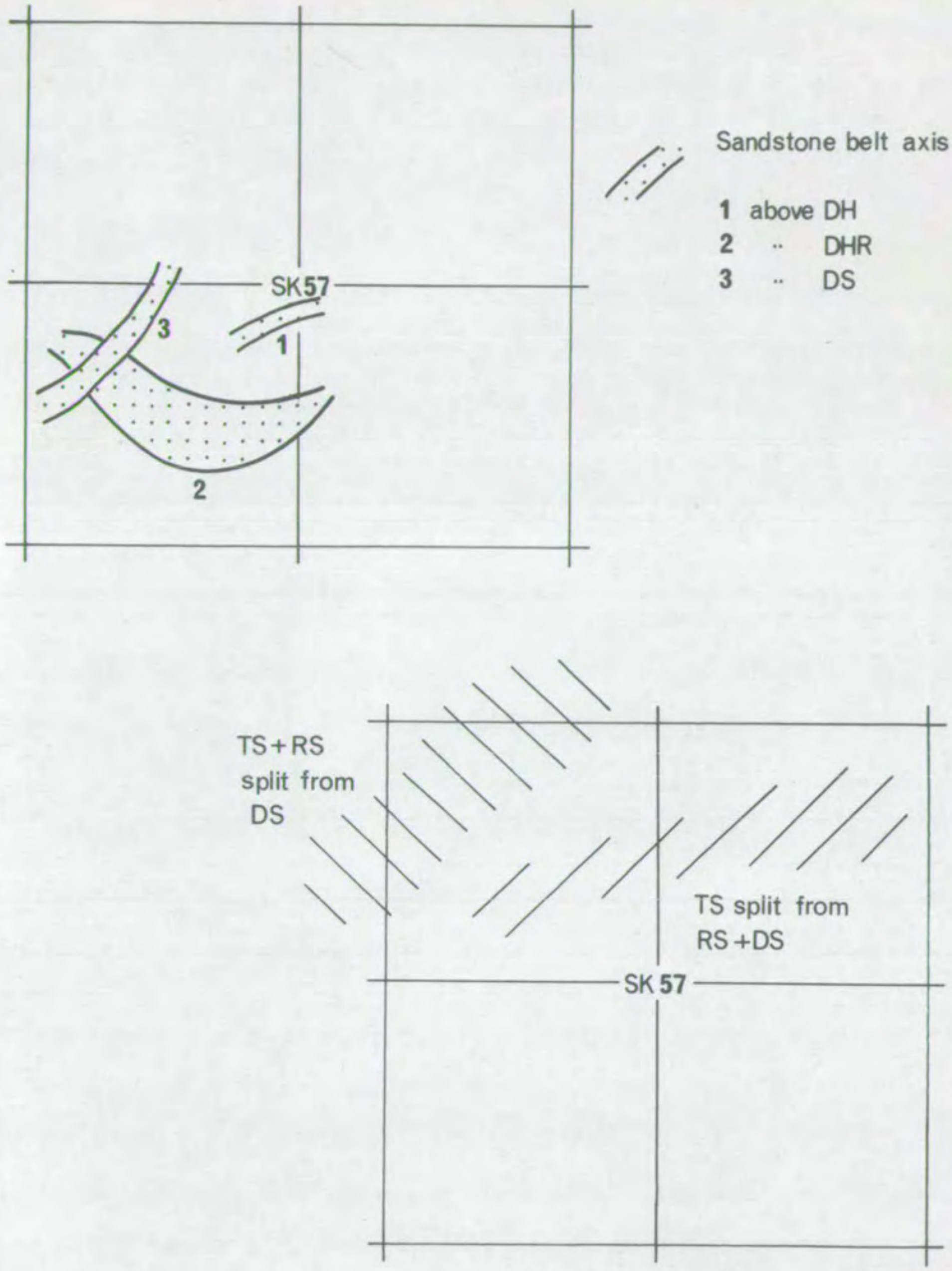
Identification of the Roof Soft coal is most difficult in the centre and North of the area, where the Deep Soft cannot always be recognised or is not developed. The simpler correlation scheme in the South was extended northwards where it was found to provide an acceptable framework for stratigraphic analysis. In 56101 the Deep Soft and Sitwell coals are almost combined. 56201 is similar, but in 56204 and 56208 the coals separate. This correlation scheme can be extended through SK56NW to SK46NE but towards the North-East the Roof Soft remains close to the Deep Soft, they eventually combine, and the Top Soft is split away.

At 47201, Smith et al (1967) tentatively suggested that the

Deep Soft is absent and that a thick Roof Soft is split away from a combined Top Soft and Chavery. Close by, however, at 47202 the Roof Soft is represented by a thick dull coal in a Flockton section. Thus at 47201 the Roof Soft has probably degenerated to a thick seatearth, a common characteristic of this coal, and what is recorded as the Roof Soft is probably the Deep Soft. Comparisons with sections of the Clay Cross Soft group in SK46SE and SK46NE support this hypothesis, and the scheme can be extended into SK57 without undue difficulty although the problem is exacerbated by the presence of superimposed sandstone bodies, figure (4.6.1).

One of the major problems of correlation of the Deep Soft coal is terminology. In the North-West the lower Clay Cross Soft member, the Sitwell, was sometimes recorded as the Eckington Deep Soft. This name was carried over to the North-East where it was applied to the combined Roof Soft and Deep Soft (D. Turner 1968, personal communication). Occasionally this new Eckington Deep Soft clearly correlates with coals recorded simply as the Deep Soft, a name which can be shown to have its correct significance only a few miles to the South. The addition of misidentifications to this taxanomic muddle made accurate correlation difficult, and it is not impossible that some of the irregularities in the isopach maps of this interval, especially in the North, arise from errors in naming coals.

The remaining correlation problems in the Clay Cross Soft group of coals can also be disposed of at this juncture. Returning to the known correlation of borehole 56101, two coals, let them be X with Y above, occur above the Sitwell. X and Y find ready equivalents in 56201 and X can be traced eastwards via 56305 where it is recorded as a cannel.



Figure(4.6.1) Sandstones affecting the Clay Cross Soft group; the areal extent of some coal splits.

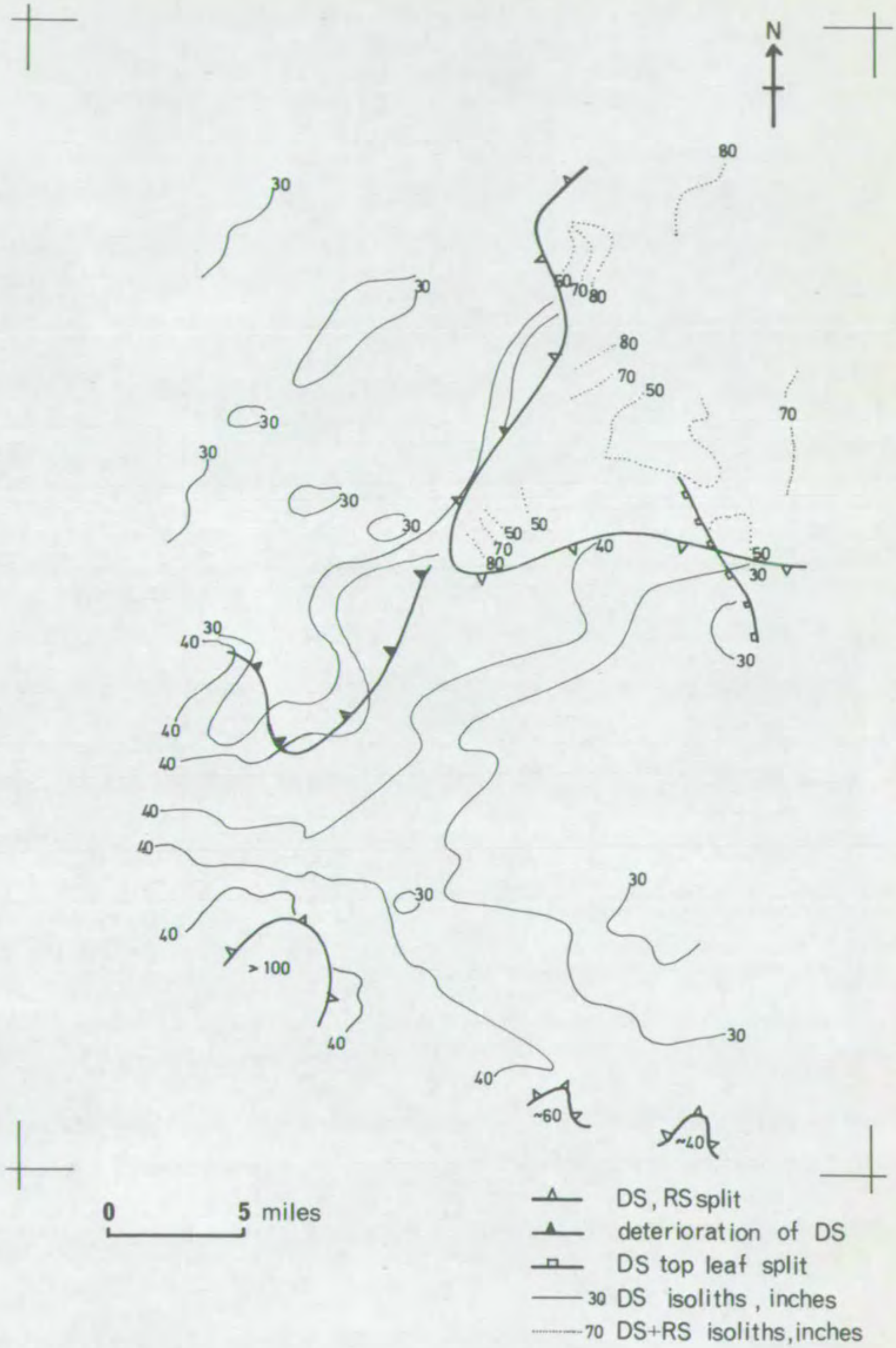
Further East X can be seen to be the same coal as the split from the "Deep Soft" recorded by Edwards (1967).

All the above-mentioned correlations are illustrated in figure (4.7.1).

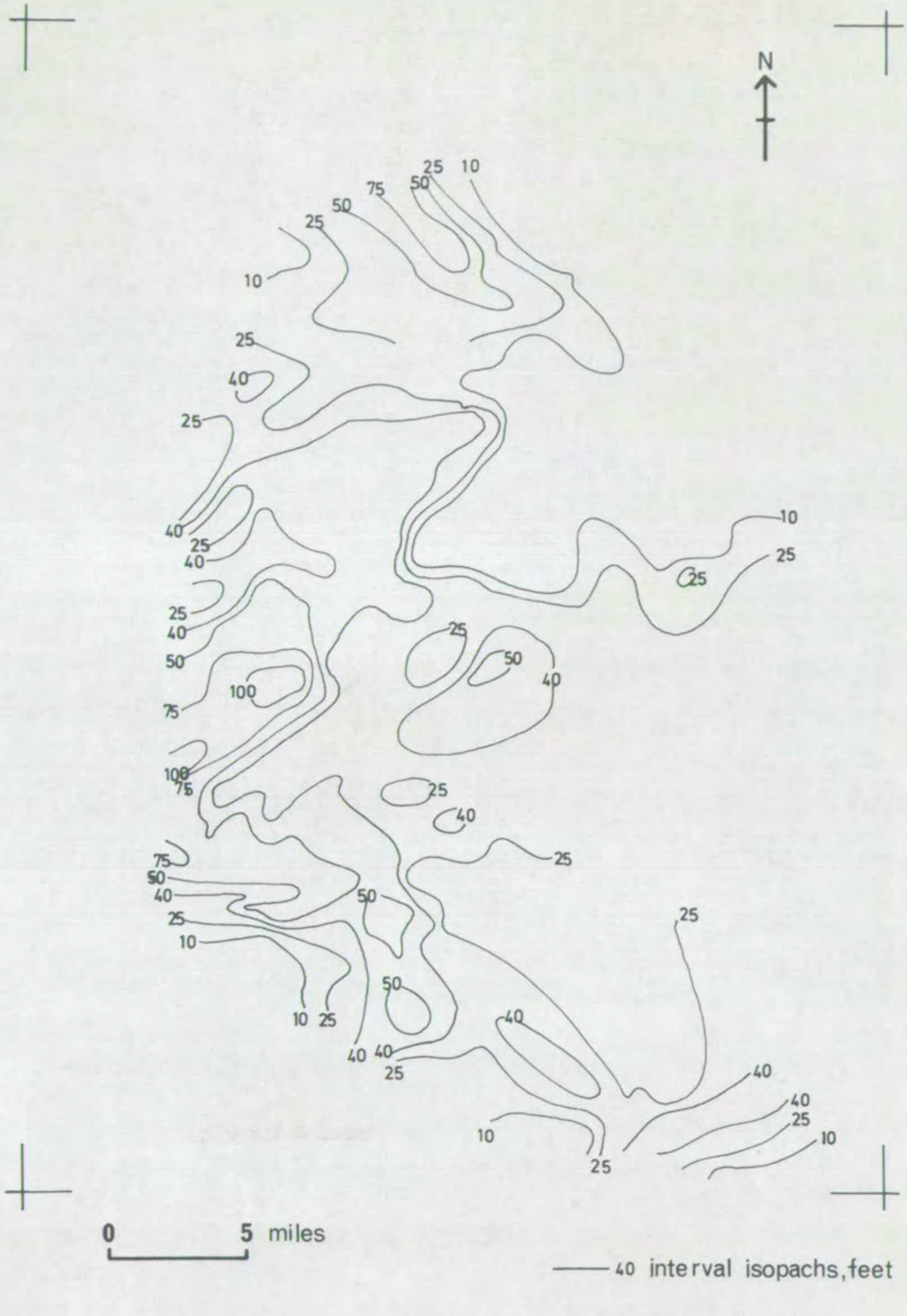
Taking the Roof Soft to include the twin horizon of cannel over bad coal, the interval consists of one cycle over most of the area. The most common intermediates occur in the North and West and are associated with the Deep Soft Rock, figure (4.6.3).

Figure (4.6.2) shows the thickness of the Deep Soft coal, in this case excluding dirt because of the error introduced by frequent splits. The simple increase in thickness towards the North-West ends abruptly along a line approximately flanking the zone of greatest thickness of the Deep Hard Rock. The thinning is accompanied but not caused by splitting and can be used to differentiate the real from the Eckington Deep Soft. The combined Deep Soft and Roof Soft coal does not thin or deteriorate over the Deep Hard Rock.

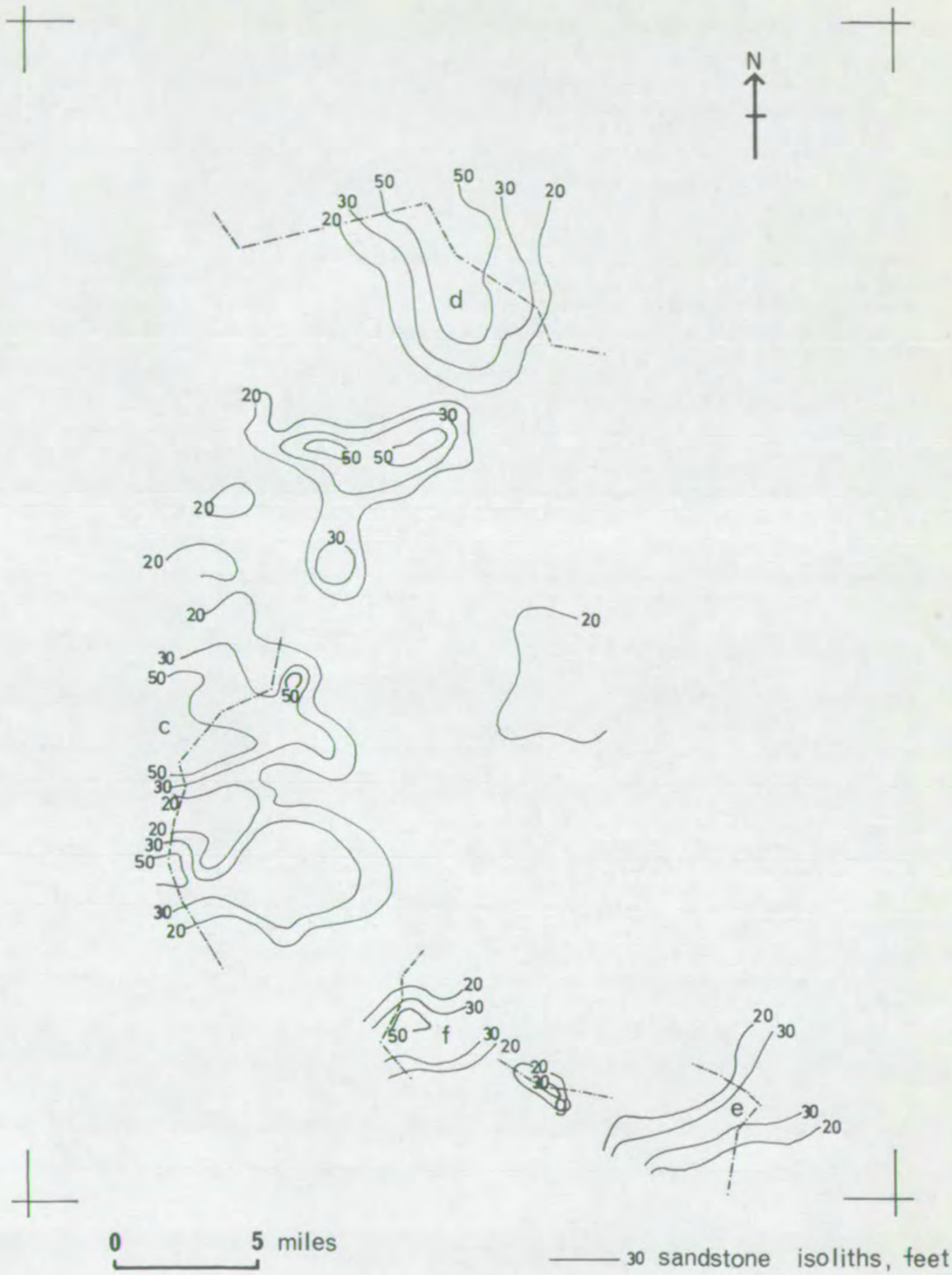
The interval is thickest in the West and North-West, figure (4.6.3), and is thinnest in the centre, South and South-West but thins to nothing where the definitive coals are combined in the North and North-East. A belt of greater than average thickness trends North-East across the North-West of the area and is associated with the thick sandstones of the interval, which consists of a string of unconnected pods, figure (4.6.4). Two other bodies of sandstone occur in the South and South-East. Both trend towards the North-East. In most cases the thick sandstones coincide with areas where the interval is thickest but occasionally the interval can exceed 80 feet without sandstone.



Figure(4.6.2) Thickness of the Deep Soft coal (DS) excluding dirt.



Figure(4.6.3) Total thickness of interval 5.



Figure(4.6.4) Thickness of sandstone in interval 5.

The effect of the interval below on the total thickness is complex and not as pronounced as seen previously. There are areas of obvious positive and negative correlation. Similarly, while the main southern pods of the Deep Soft Rock are displaced to the South of the main belt of the Deep Hard Rock, further North the trends intersect and areas of increased sandstone thickness coincide.

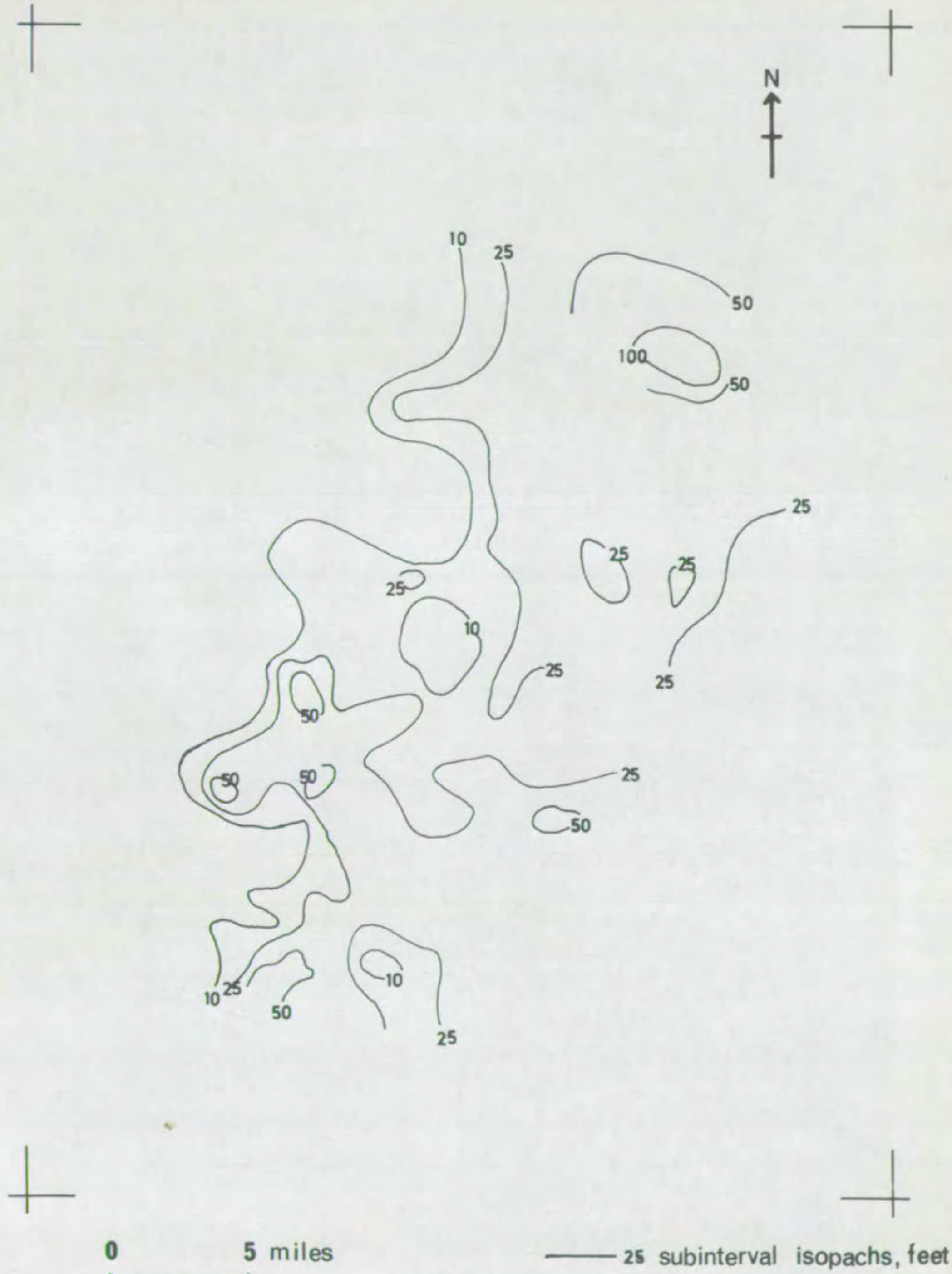
4.7 Roof Soft to Chavery Coal, Interval 6

The Roof Soft coal, which forms the lower boundary of this interval, can be traced over most of the map area. The upper boundary is in theory the Chavery coal but in practice the Black Rake coal was used as a substitute where the Chavery was absent. The error introduced in this way is very limited because the Chavery and Black Rake coals and seatearths comprise a twin horizon wherever recorded together. The interval can be subdivided into two parts using the Top Soft coal.

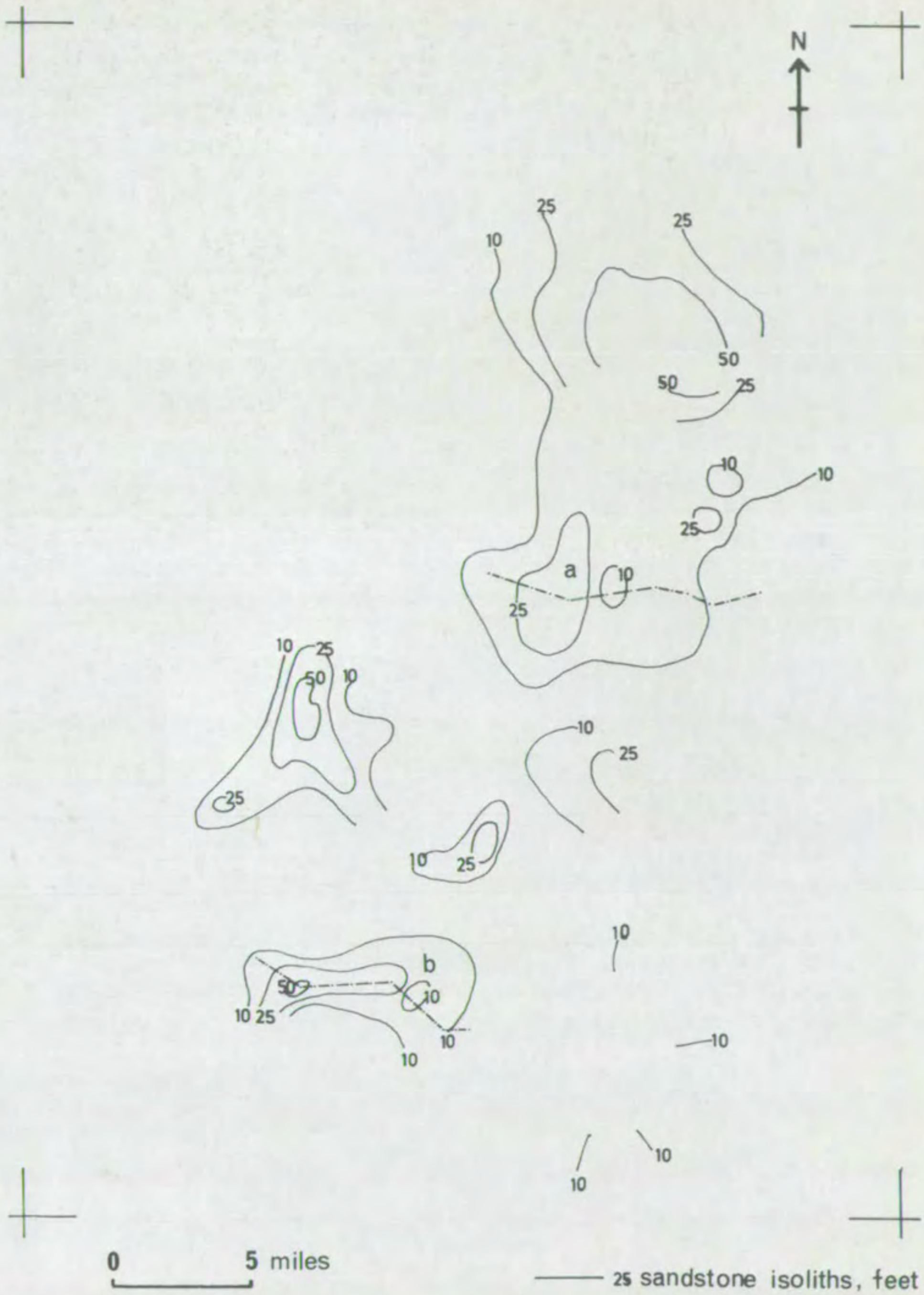
The Roof Soft coal, figure (4.7.1), thickens progressively towards the North-West. The trend ends abruptly along a line orientated North-East to South-West, which approximately follows the southeastern margin of the string of sandstone pods of the Deep Soft Rock.

The lowest subinterval is confined to the South-East of the map by the junction of the Roof Soft and Top Soft coals in the North-West. The line of the southeastwards split of these coals corresponds to the south-eastern margin of the Deep Soft Rock. The thickness of the

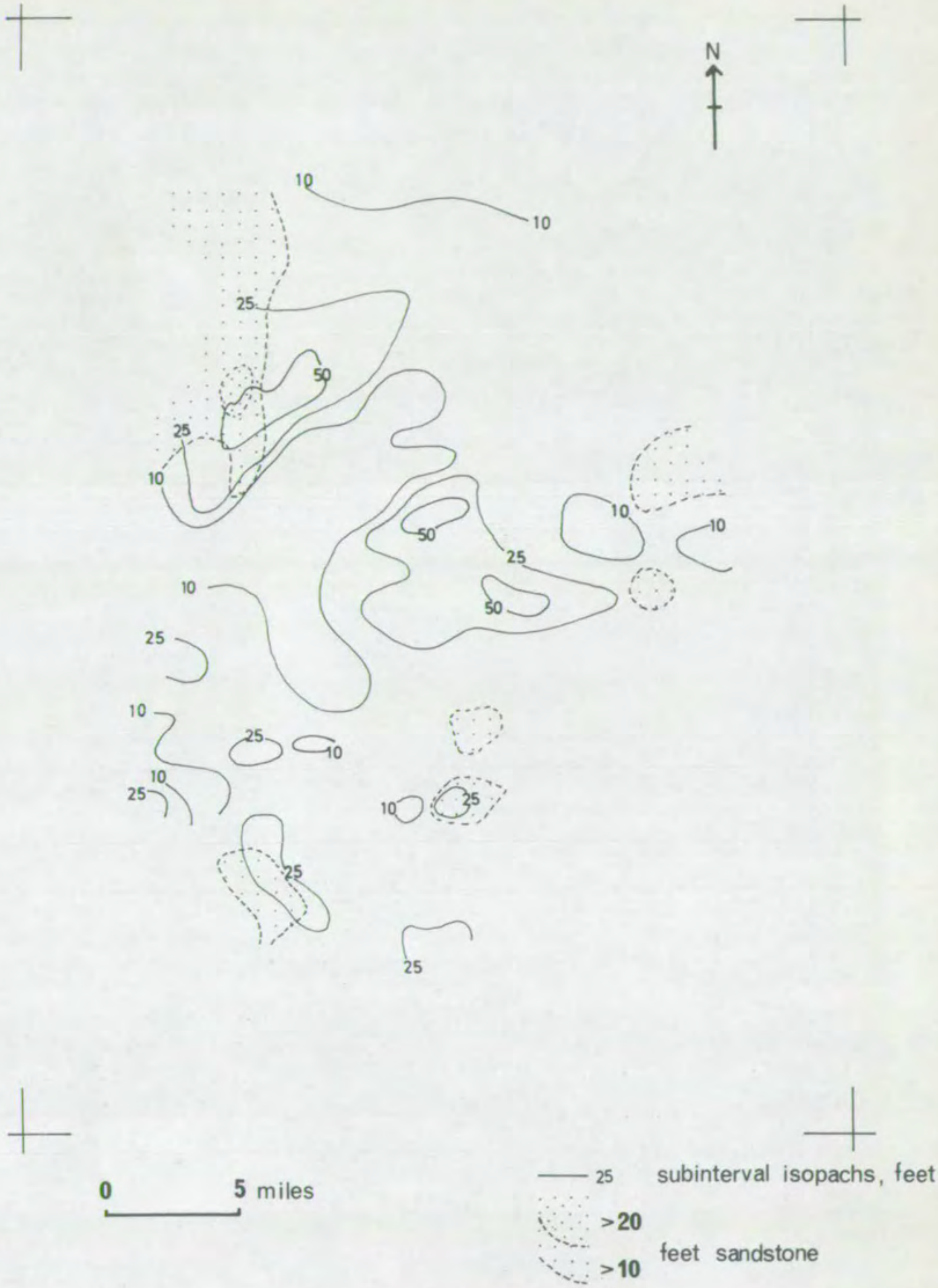
Figure(4.7.1) Thickness of the Roof Soft coal (RS) excluding dirt.



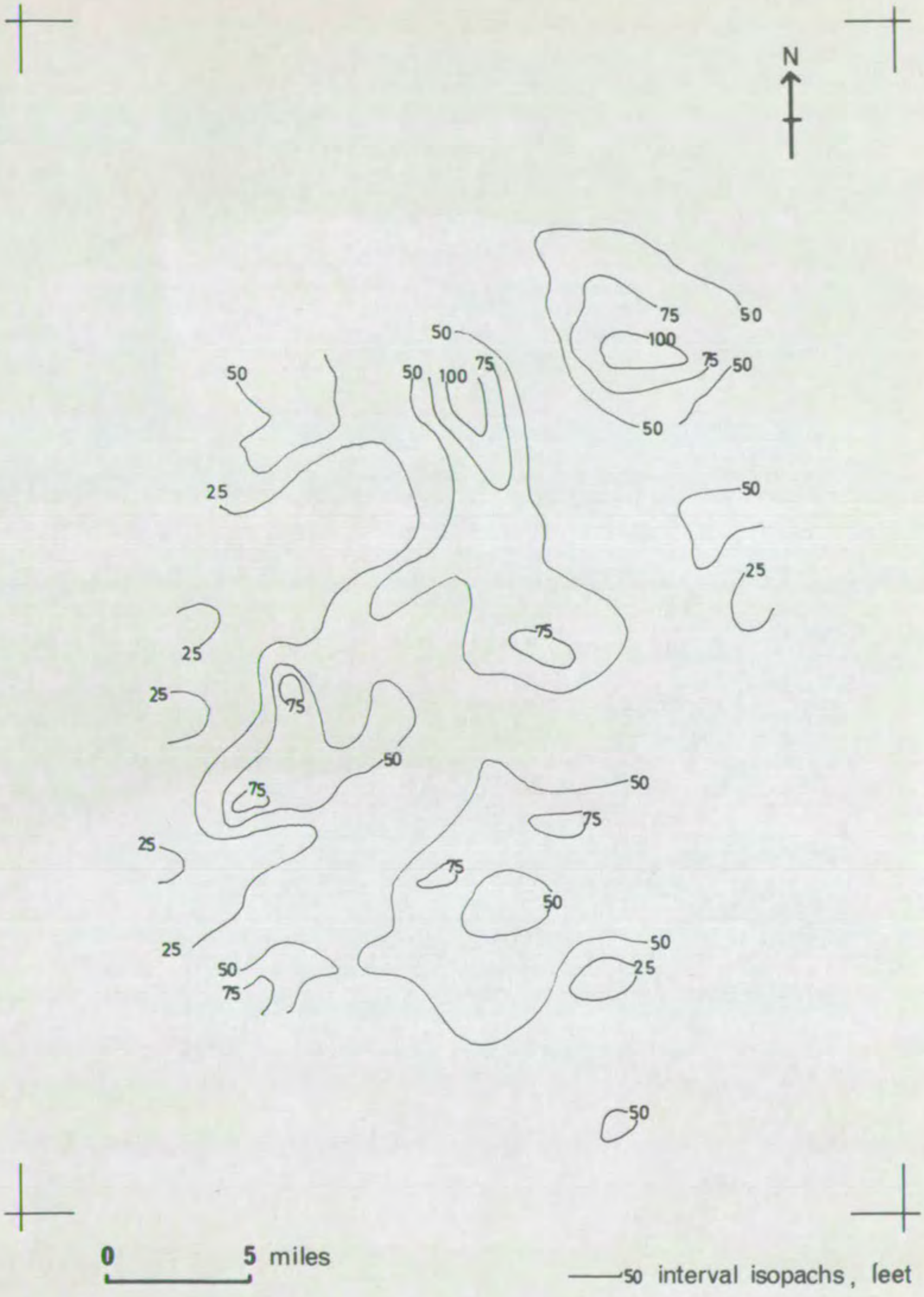
Figure(4.7.2) Total thickness of the lower subinterval of interval 6.



Figure(4.7.3) Thickness of sandstone in the lower subinterval of interval 6.



Figure(4.7.4) Total and sandstone thickness of the upper sub-interval of interval 6.



Figure(4.7.5) Total thickness of interval 6.

subinterval, figure (4.7.2), is very irregular and clearly reflects the distribution of the sandstones, figure (4.7.3). The sandstones of the subinterval consist of pods which appear to lie in a belt trending North-East. However, there is scant evidence to prove that more pods do not occur in the East and South-East.

The overall pattern of total and sandstone thickness of this subinterval shows some obvious inverse relationships with the thickness patterns of interval 5. In detail, however, the picture is confused and it is impossible to make any generalised statement regarding the influence of the preceding interval.

The thickness of the top subinterval, figure (4.7.4), has no regional element in that it bears no relationship to Wills'(1956) isopachs. There appears to be no relationship with the lower subinterval. The sandstones are thin and scarce, a maximum thickness of 36 feet being recorded amongst scattered pods, figure (4.7.4). There is apparently no correspondence between total and sandstone thickness.

The total thickness of interval 6, figure (4.7.5), shows an offset of maxima from the interval below. Unlike many previous negative correlations there is no contribution from the relative positioning of sandstone.

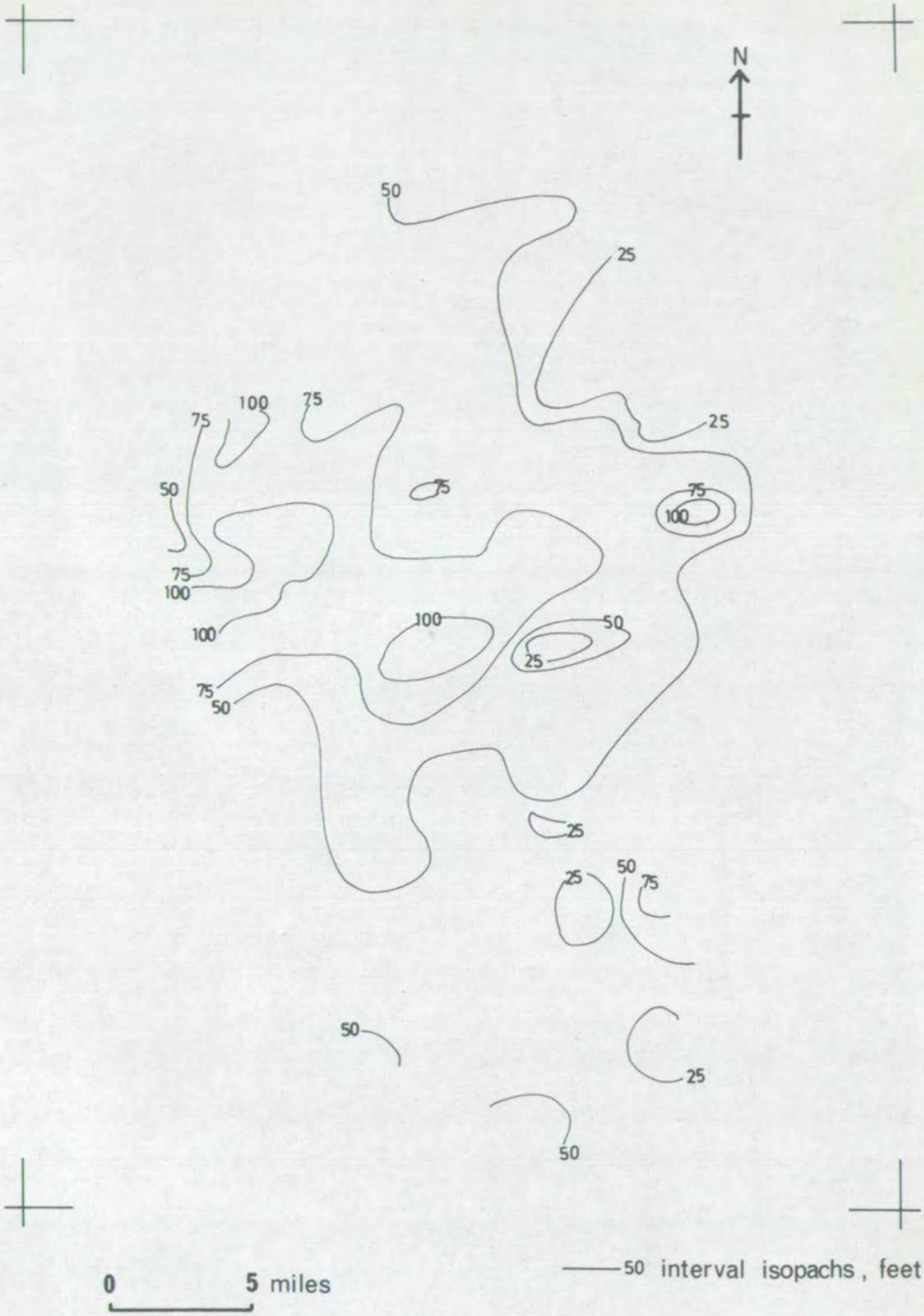
4.8 Chavery Coal to Clay Cross Marine Band, Interval 7

The base of the interval was taken as the Chavery or Black Rake coals, as discussed above. This is a reasonably easy horizon to locate because it is succeeded by a prominent ironstone. The top of the interval was taken as the base of the Clay Cross Marine Band. This horizon is, therefore, defined by the transition from brackish, or fresh, water to marine fauna. Fortunately the downward transition from the marine acme is much sharper than upwards (Calver 1968). Over most of the northern part of the area the marine band rests on the Joan coal. The Joan horizon can be traced southwards and some recent records have been used to show that it remains in close combination with the Clay Cross Marine Band, figure (3.0.3). In some older records the top of the interval was, therefore, taken as the top of the Joan coal or seatearth. The maximum error introduced in this way, in the centre of the area, was about 20%.

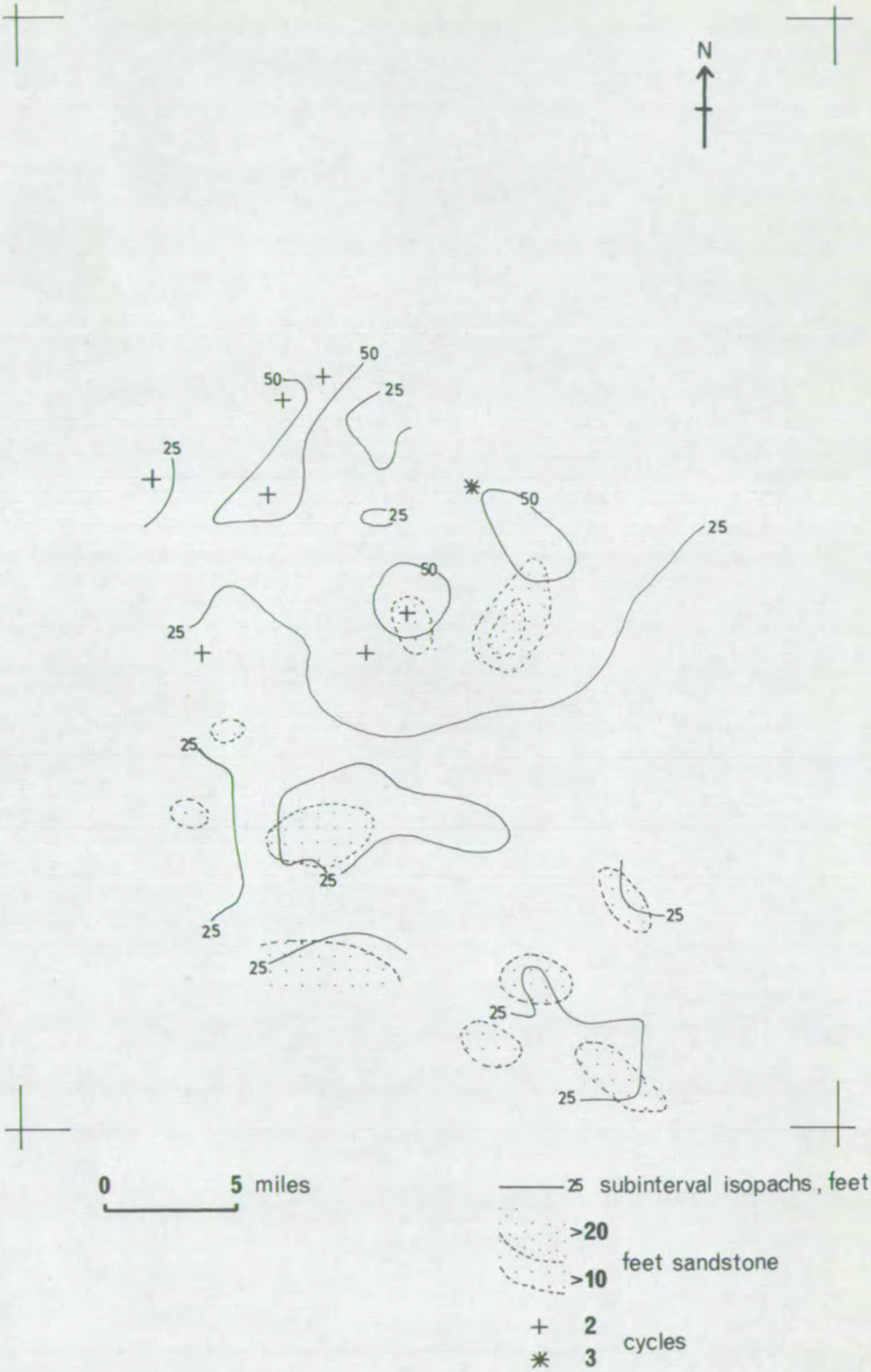
The interval is divided into two subintervals by the Brown Rake coal. This horizon again is a twin and is associated with an overlying ironstone. No coal thickness maps can be produced because of the duality of the data.

The thickness of interval 7, figure (4.8.1), increases towards the North-West and the pattern reflects Pennine Basin palaeogeography. Complexities arising on the scale of a single observation probably arise from misidentification.

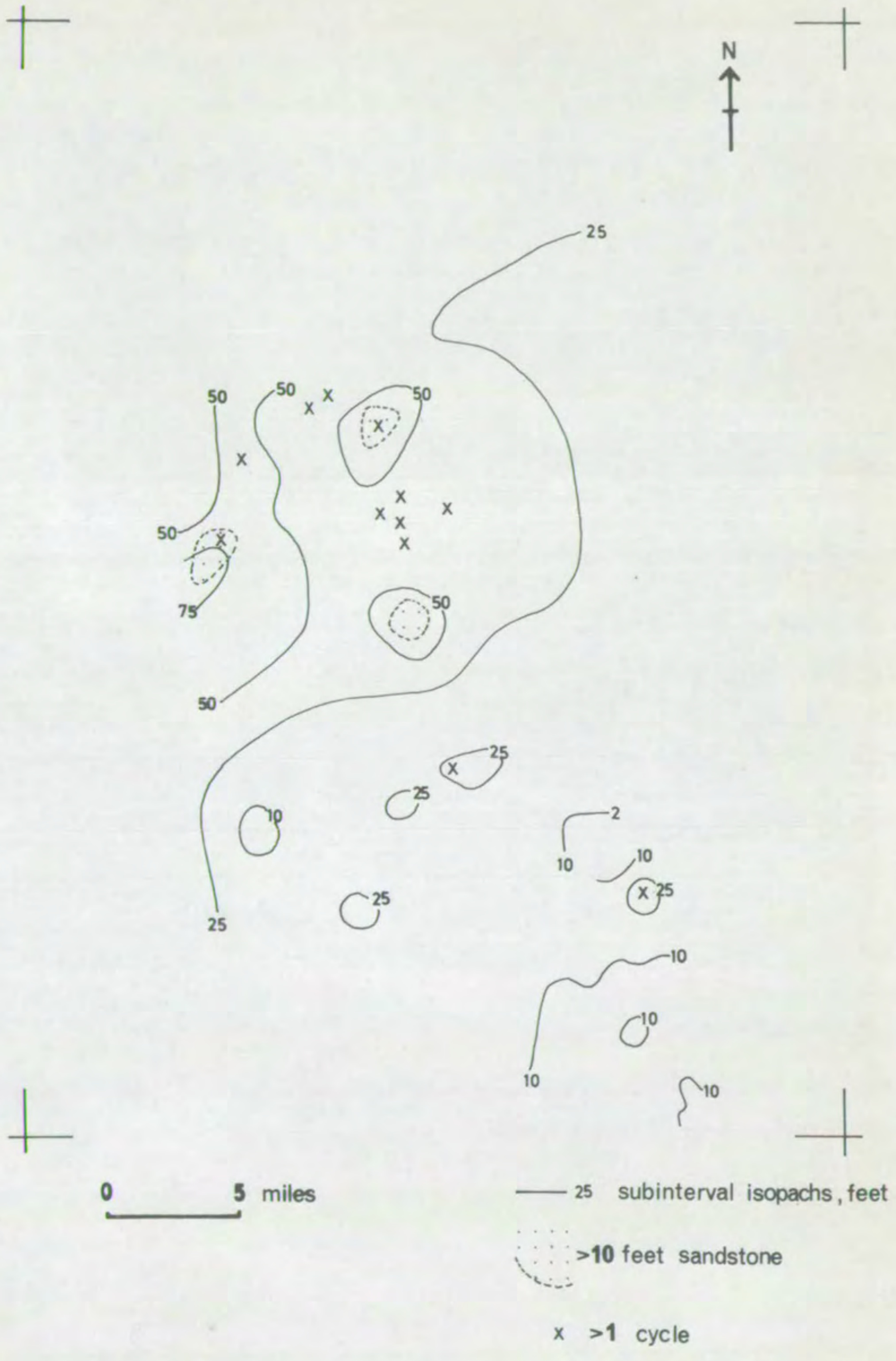
The thickness of the lower subinterval, figure (4.8.2), bears no obvious relationship to the overall pattern mentioned above. However, the subinterval reaches its maximum development in the North. The sandstones are thin and restricted to small scattered pods occurring in the South of the area. A few intermediate thin coals and seatearths give



Figure(4.8.1) Total thickness of interval 7.



Figure(4.8.2) Total and sandstone thickness of the lower sub-interval of interval 7.



Figure(4.8.3) Total and sandstone thickness of the upper sub-interval of interval 7.

rise to increasing complexity towards the North-West and are, therefore, not associated in any way with the sandstones.

The pattern of thickness of the upper subinterval, figure (4.8.3), strongly resembles the supposed contours on the depositional slope, section (3). Sandstones are again rare and thin, but occur in the North-West and are associated with increases in complexity arising from ephemeral intermediate coals and seatearths.

The upper and lower subintervals, therefore, have a positive correlation, arising in patterns which reflect the thickness of the Coal Measures as a whole. However, there is notable inverse proportionality between intervals 6 and 7, arising principally on the small scale.

4.9 Synthesis and Conclusions

The detailed analysis was carried out on the basis of a simple division into sand, clay and coal, because the poor quality of some of the older lithological descriptions, and the extent of operator error in recent records, did not warrant a further subdivision of sediment types. Comparisons of total, sandstone and coal thicknesses of intervals with their neighbours, and with the Pennine Basin as a whole, have permitted the following general conclusions to be reached.

The total thickness of intervals or subintervals sometimes shows a tendency to increase towards the North-West of the map area and, therefore, towards the centre of the Pennine Basin. In other intervals the zone of maximum development is confined to the map area and, therefore, local with respect to the whole basin of deposition.

In many areas there is a direct or inverse proportionality between the thicknesses of adjacent intervals or subintervals. Most positive correlations arise on the large scale where the intervals show some relationship to the basinwide subsidence pattern, section (3). Negative correlations appear to arise on a smaller scale, usually confined to the map area, and are usually not persistent through more than one interval.

The relationship between total interval and sandstone thickness is generally quite strong. Duff and Walton (1964) showed that the correspondence arises, at least partly, on the very large scale, although this result is affected by the closed number system employed. The stratigraphic analysis shows that, in general, where the interval is thickest, on the small scale, it contains a thick sandstone. Clearly compaction contributes towards the coincidence but the occurrence of thick non-sandy and thin very sandy intervals and subintervals suggests that there may be other factors involved.

There is a tendency for the sandstone bodies of adjacent intervals to be offset from each other, and yet to remain close together and, where they are elongate, to have parallel trends. However, there are examples of the coincidence of local thickness maxima.

Total coal thickness, including dirt, increases towards the North-West, probably at the individual seam level, and, therefore, shows a fairly strong basinal component. The simple pattern is usually interrupted by the presence of an underlying thick sandstone. The coals sometimes split towards these sandstone bodies and usually thin and deteriorate over the axis of maximum thickness.

There are some examples of the correspondence of coal and overlying interval thickness. The relationship is complex and never consistent over the whole area, and probably arises from the interaction of interval thicknesses.

Ignoring interval 1, there is a progressive upward change from sandy intervals, with non-basinal thickness distributions, to basinal non-sandy intervals. There is a concomitant increase in the frequency of occurrence of non-marine bivalves and ironstones, and the substitutions of seatearths for thick coals. This trend apparently culminates in a marine incursion. Since the Clay Cross Marine Band (Anthracoceras Vanderbeckei Ludwig) can be traced more or less throughout northern Europe, a general synthesis would be required before the significance of this trend could be evaluated.

The observed areal variations and interactions provide a means of identifying the mechanisms involved in the build-up of the Coal Measures. The areal extent of these processes should be reflected in the extent of their effects. Since the size of the Pennine Basin has been defined (Wills 1956) it is possible to differentiate between processes which operate on the scale of the whole basin, or on a smaller or larger scale. In this way an initial, perhaps tentative, identification can be made. For example, the embryo movements of Armorican folds would produce small-scale variations.

Further evidence can be produced if the shapes and orientations of processes can be defined. Using the same example, the effects of folds would tend to be elongate with a Charnoid trend (Smith _et al_ 1967). The permanency and interaction of the processes can also be used; the influence of a fold should be restricted to one area through time although it might only be intermittently operative.

However, at this stage the evidence consists merely of subjective qualitative statements based on isopachyte maps which may be of doubtful significance (Dodd _et al_ 1964). The information was, therefore, subjected to statistical analysis so that the sizes of the various components could be separated and measured. The relationships, established subjectively in this section, were then statistically tested at different scales. Positive statements can then be made, about the existence of similarities and differences, with a known probability of being in error. These quantitative comparisons form the substance of section (6).

Trend surface analysis is tailor-made for the purpose of separating the scale components of areal variability. However, doubts have recently been cast on the usefulness of the application of this technique in geology (Meisch and Connor 1967, Middleton 1967). Because this technique is essential to the subsequent analysis a discussion of the application of the method is presented in section (5).

TREND SURFACE ANALYSIS

5.1 Introduction

Trend surface analysis can be attempted in a variety of ways but the most common are based upon a general linear model and use simple power series. Fourier and other transformations can be made but, like the non-linear models suggested by James (1967), unless there is some _a priori_ reason for selecting one in particular, testing a range for applicability would be prohibitively expensive; however, see Miesch and Connor (1968).

Like most quantitative techniques trend surface analysis has come in for its share of criticism. Objections tend to fall into two groups, as characterised by Miesch and Connor (1967), who considered that since surfaces are by nature empirical they may never be interpreted in a useful way without heavy reliance on other geological information, and by Lee and Middleton (1967), who doubted whether any application "to date" had produced anything which could not have been extracted from the raw data; however, they did not describe any method which could be substituted for trend surface analysis.

Justifiable or not, these criticisms arise principally for two reasons: 1) the bias of the data presented for analysis; 2) the lack of a precise definition of objectives and, therefore, a guide for interpretation. The discussion of these factors involves a number of terms and concepts which it is necessary to define.

A least squares trend surface is by definition the best of any given complexity that can be fitted to the data. If the deviations (the differences between observed and computed values) are uncorrelated then the surface is said to be a maximum-likelihood predictor. Grant (1957) reduced this constraint to the assumption that the co-variance amongst deviations with zero mean could be neglected compared to that of the trend. However, most geological information is very noisy and it is unlikely that low complexity surfaces could fulfil this requirement.

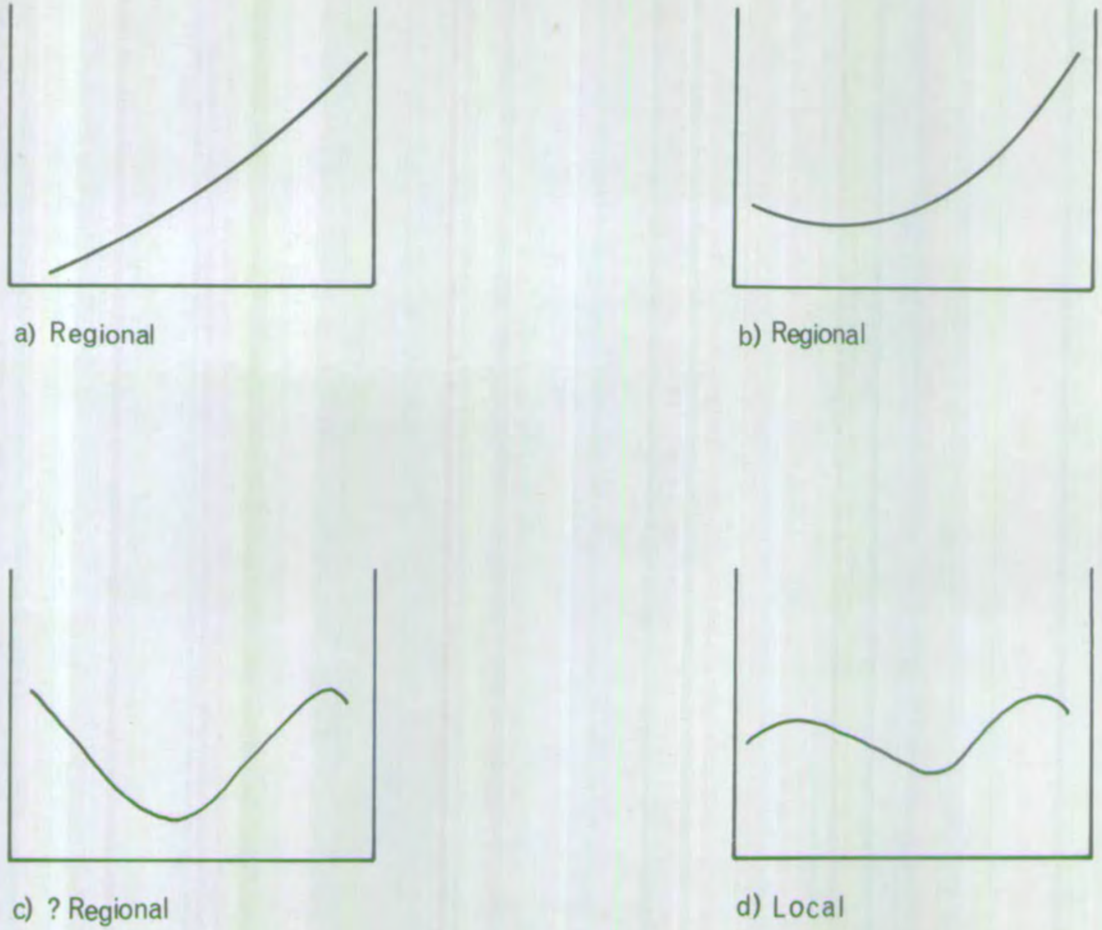
The concept of noise can be most naturally studied if geological data is considered to consist of <u>three</u> components, regional, local and residual, rather than just <u>two</u>, regional and error. If trisection is accepted the three components can be rigorously defined in terms of the map area and number of observations. Their uncritical use causes confusion and even Grant (1957) advocated the discontinuance of the term 'regional'.

The exact meanings used in the following discussion are given below.

a) regional - a response to a process (or processes) which operates over an area greater than that under investigation and without repetition within the map limits.

b) local - a response to a process (or processes) which operates over an area less than that under investigation but greater than the average area associated with any observation. This 'mean' or 'effective' area is defined as the total map area divided by the number of observations.

c) residual - a response to a process (or processes) which operates over



Figure(5.1.1) Suggested complexity limits for regional components.

an area less than one effective area. Residuals are by definition uncorrelated since no two observations can refer to any individual response.

The definition of the regional component suggests that simple complexity limits may be described. Examples are given in figure (5.1.1) for sections across maps.

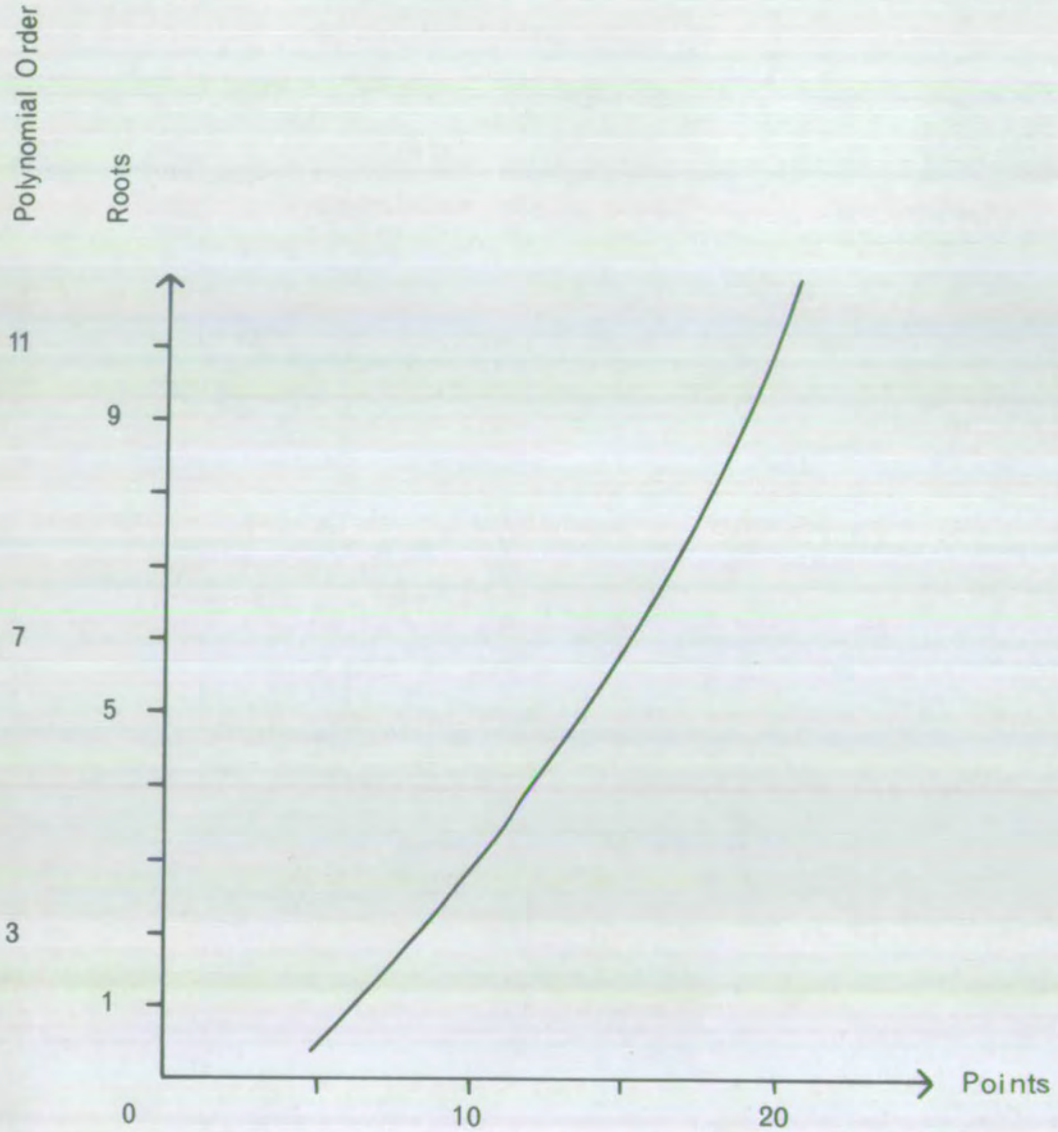
In the following discussion the problems of input and sample size and distribution are considered before those of interpretation.

5.2 Sample Size

The size of most areally distributed geological samples is controlled by the amount and quality of information available. Acceptable minimum limits are usually defined by the objective of the exercise; for example, the effective area must be smaller than that of the particular phenomenon under investigation.

However, it is also necessary to take sample size into account when assessing the inference of a trend surface. Minimum statistical requirements can be obtained in the same way as in the analysis of time series, since these can be equated with space series (Matheron1962, Preston 1966, Agterberg 1967).

In the simplest case a rectangular control grid can be considered as two sets of intersecting space series inclined at right angles. In any one series of 'n' individuals the mean 'mp' and variance 'sp' of the number of turning points 'p' are given by Yule and Kendall (1958,



Figure(5.2.1) Dependence of the maximum number of turning points for a non-random series on the number of members.

p.638) to be approximately

$$mp = 2.(n - 2) / 3$$

and $$sp = (16.n - 29) / 90.$$

If the series has p_o turning points then

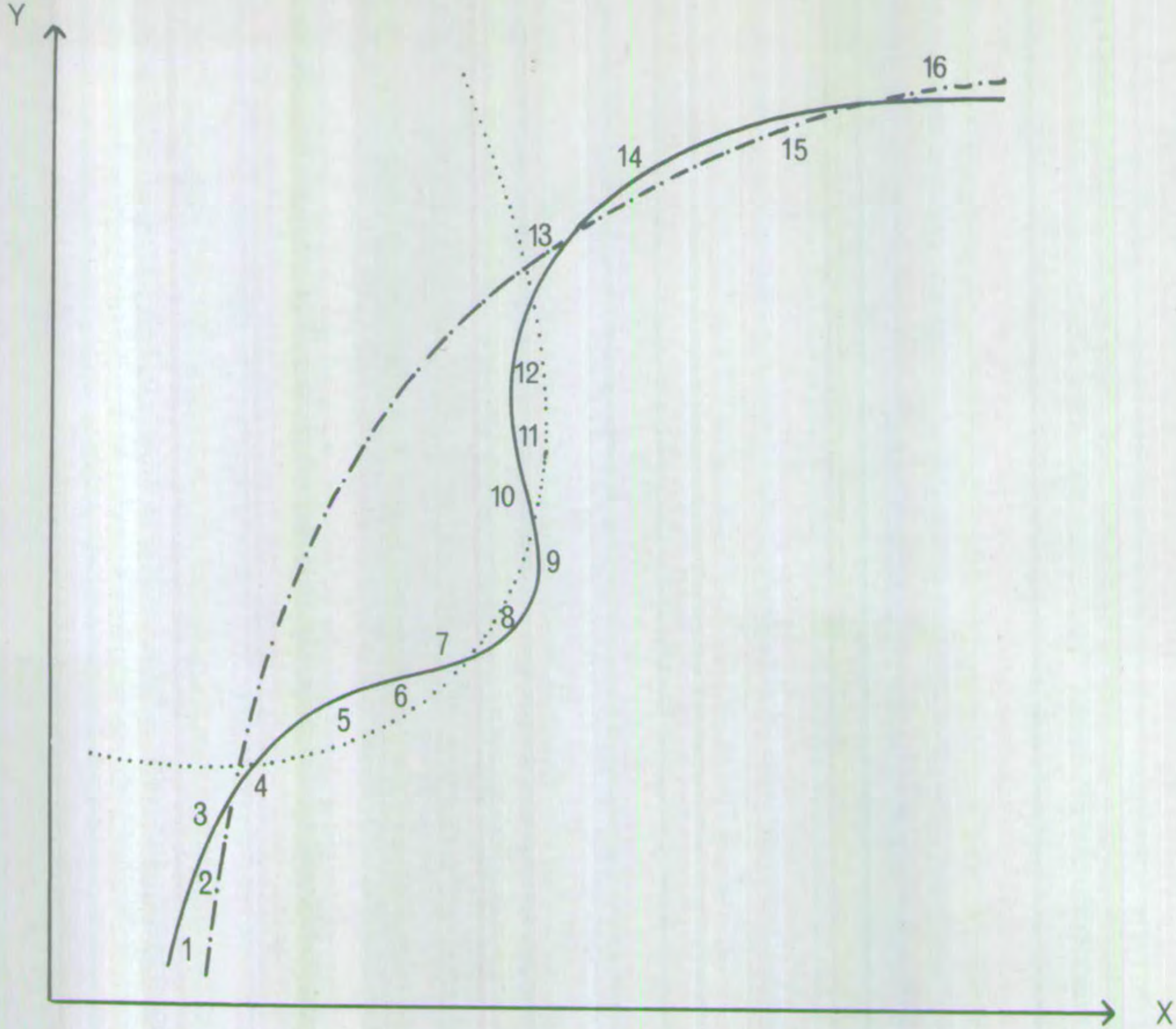
$$p_o < mp - 2\sqrt{sp} = f(n)$$

if the series is to be considered non-random. The dependence of f(n) on n shown in figure (5.2.1.).

Since any map section has only one degree of freedom with respect to the co-ordinate system, the partial derivative of a polynomial of order 'k', formed where one co-ordinate is considered constant, will have a maximum of k - 1 real roots and, therefore, k - 1 turning points. It follows that a polynomial section with f(n) turning points must be constructed from more than n observations if it is to be considered non-random. A polynominal of order f(n) + 1 must be computed over a square grid of (n x n) observations if likewise we are to be sure that it could not arise by chance alone.

From figure (5.2.1) it is not justifiable to produce, for example, a quadratic trend surface from less than about 50 control points nor a cubic surface from less than about 80. There seems to be no _a priori_ reason for not extending these conclusions to include non-rectangular distributions.

According to Agterberg (1967) the number of observations can also affect the fit of the regression to the data. Practically this factor produces such small differences that it can be ignored; the results of a simulation test described in section (5.3) illustrate this point.



Figure(5.3.1)

5.3 Sample Distribution

McIntyre (1967) stated that if trend surface analysis is to be justified in terms of maximum likelihood then the data collection localities must be independent of each other. Furthermore, the sampled population must be an unbiased sample of the underlying target population if a trend surface is to have any practical significance. It appears that a bad distribution of control points is likely to be a more serious consideration than the defence of the principle of maximum likelihood.

The sampling problem can be described with reference to the simple two-dimensional analogy illustrated in figure (5.3.1). Using the full set of observations a perfect fit could be obtained from a quartic regression line. However, different quadratic regression lines, also with perfect fit, would be obtained if subsets (1, 2, 3, 4, 13, 14, 15, 16) and (5, 6, 7, 8, 9, 10, 11, 12) were used. The cause is bad sampling and the result the difference between real and apparent regression lines.

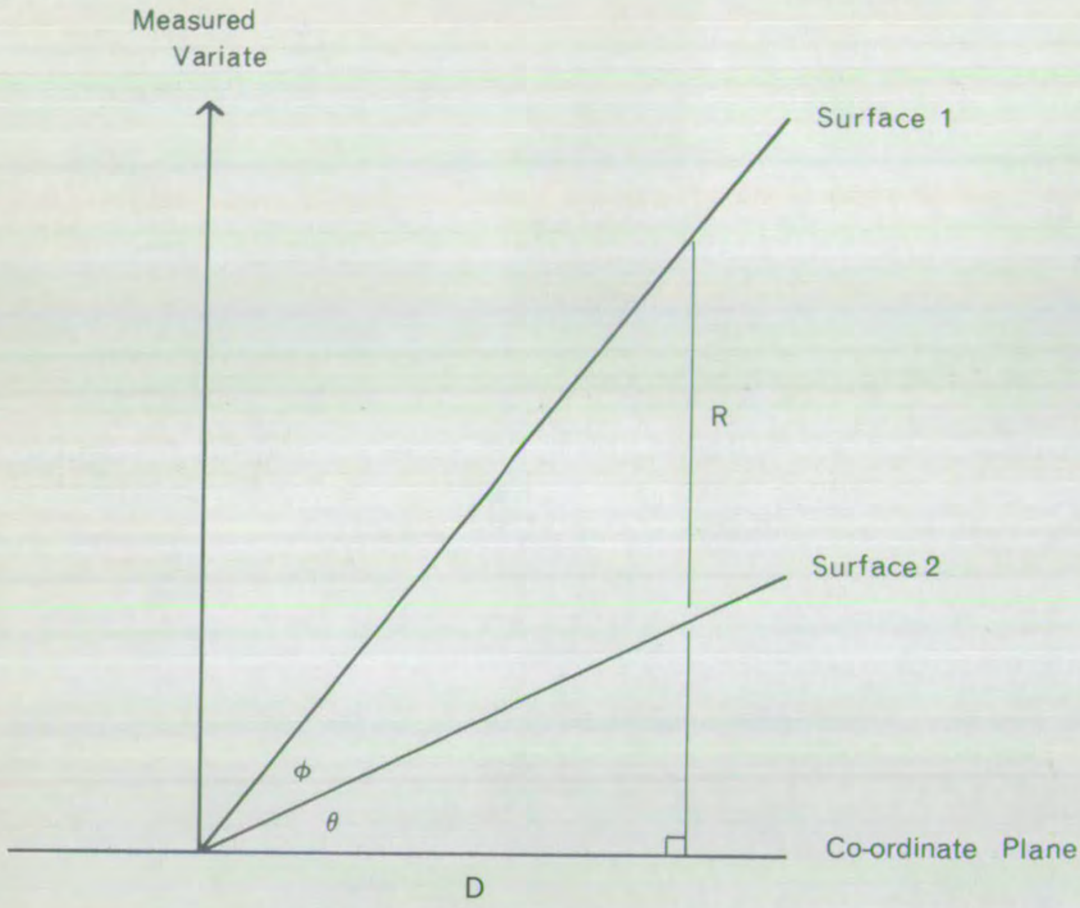
In three dimensions it is, therefore, possible that trend surfaces can be distorted by clustering of data collection points or by correlation between their map co-ordinates, which gives rise to linearity in the distribution. There are two sources of linearity.

'Type 1' was recognised by Krumbein (1960) and arises from the restriction of the control area, or the smallest area containing all the data collection localities, to a strip across the map. 'Type 2' is more obscure and arises where there is a tendency for the localities to cluster about a line within the control area, whatever its shape. However elongate the control strip, trend surfaces may be statistically meaningful if there is no Type 2 linearity, because changes in scale do not alter the correlation between observation locality co-ordinates, where these are computed with respect to the control area. This point is illustrated in the results discussed below.

The restriction of the control area to a map strip is one of the principal causes of the misuse of trend surface analysis. Results which may well be statistically significant within the control area are strained to include the whole study area. Amongst others, notable examples can be found in Chorley (1964), Vistelius(1967), Earley and Goodell (1968), Tinkler (1969), Hall (1969) and Knowles (1966). The last named may be taken as an example where process and response can be misidentified. If, for example, the interplay of structure and topography gives rise to a biased outcrop and, therefore, sample distribution, the trend surfaces produced will show some correspondence to the structural pattern, suggesting some genetic relationship, whatever characteristic has been measured.

In order to measure the effects of linearity and clustering, it is necessary to measure the departure of the distribution from uniformity and the distortion of the resulting trend surfaces by comparison to some standard.

Comparison of surfaces can be accomplished using the polynomial coefficients or point samples from the surfaces; in the latter case statistical significance can be tested using the correlation coefficient possibly modified as in Mirchink and Bukhartsev (1959). However, Merriam and Sneath (1966) have pointed out that, in the application of



$$R = (\tan(\theta + \phi) - \tan\theta).D$$

Figure(5.3.2) To show that the separation of two trend surfaces is dependent upon their absolute slopes.

such methods, the assumption has to be made that the individual readings are independent, whereas in fact they are related by the trend. Merriam and Sneath's (1966) taxonomic distance uses the polynomial coefficients for comparison. Although this method is more attractive, from the standpoint that all features of both surfaces are included, it can only be used to compare polynominals of like order.

Another criticism of any technique based on point samples is that differences are measured by subtraction in one fixed direction. From figure (5.3.2) it can be seen that the difference varies not only with the angle between the surfaces but also with their absolute slope. Correction of this factor would be excessively time-consuming and expensive.

The nearest neighbour technique, described by Miller and Kahn (1962), can be used to test for clusters within the control distribution. The method was not used because of the huge amount of computer time necessary to handle large samples. Cadigan (1962) has suggested an alternative method for describing the randomness of regionally distributed data which employs the chi-square statistic. Direct application of this method would be statistically unsound because, unless the distribution is uniform anyway, it is impossible to guarantee that the minimum expected frequency per cell (5) will always be exceeded. Comparison to a regular distribution, where all cells have equal expected frequencies, could be substituted but the technique also suffers in that the result will partly be a function of the cell area employed (Evans 1952).

Since there appears to be no simple and inexpensive way of measuring clustering it is perhaps fortunate that the results described below show that for practical purposes the distortion involved is negligible.

Both sources of linearity can be measured using the sample correlation coefficient if care is taken to ensure that the correct co-ordinate system is used when describing Type 2. In this case the reduced major axis of the distribution (Kermack and Haldane 1950) should be taken as the abscissa and the centre of gravity as the origin. As long as the two regression lines are not coincident with the reduced major axis the correlation coefficient is defined.

Two artificial tests were designed to estimate the distortion arising from each type of linearity. The second simulated geological sampling distributions.

5.3 (a) Test 1

The object of the first part of this exercise was to estimate the effect of restriction of the control area to a map strip. A random distribution of 50 points over a square grid was generated from random number tables. The purely regional structure to be simulated was taken to consist of an inverted cone with its apex at the map centre. Data values associated with each point could, therefore, be computed as a constant multiple of the distance from the map centre. This data set can be referred to as 'the standard'.

The reduced major axis of the distribution was computed and the sample localities progressively clustered about it. For each new distribution, the data values were computed in the same way as the standard, so that the information was always a sample from the surface of the cone. The data, therefore, always contained the same <u>real</u> regional component, so that any divergence of the <u>apparent</u> trends produced can be considered as a function of the relative distribution of the control points, and not the result of using different combinations of data containing different real components, as in figure (5.3.1).

The correlation coefficient measured with reference to the reduced major axis remained small and insignificant, table (5.3.6), so that there was no contribution from Type 2 linearity.

Clustering about a line within the control area was studied in a similar way, except that 15 of the points, spread evenly over the map, were not progressively grouped. The map and control areas, therefore, remained constant throughout so that there was no additional influence from Type 1 linearity.

Linear and Quadratic trend surfaces were computed from the eleven different data sets. Table (5.3.3) shows that while all the quadratic surfaces fitted the data very well, linear surfaces explained 10% or less of the variation. The insignificant linear fits reflect the complete absence of any linear trend component from the data, except where it arises from rounding errors. The quadratic fits were not perfect because some noise was introduced by rounding data values to integers.

Figure (5.3.4) shows the progressive distortion of quadratic surfaces drawn over the distributions simulating Type 1 linearity. Correction in this case could be accomplished by simply rescaling the ordinate directed perpendicular to the reduced major axis, but this cannot be

Co-ordinates referred to reduced major axis.	% Sum of Squares Explained	
	Linear	Quadratic
Test 1		
Standard (u,v)	9.2	95.6
(u,3v/4)	10.3	94.9
(u,v/2)	10.8	91.5
(u,3v/8)	9.7	93.2
(u,v/4)	9.1	92.9
(u,v/8)	8.5	92.4
Test 2		
Standard (u,v)	9.2	95.6
(u,3v/4)	9.4	94.7
(u,v/2)	9.6	92.0
(u,3v/8)	8.2	93.6
(u,v/4)	7.1	93.5
(u,v/8)	5.9	92.9

Table(5.3.3)

Figure(5.3.4) Progressive distortion of a quadratic trend surface under the increasing influence of Type 1 linearity. Linearity created by reduction of the 'v' co-ordinate (orthogonal to the reduced major axis (r) which is the 'u' axis) for all points in the distribution.

1 (u,v)
2 (u,3v/4)
3 (u,v/2)
4 (u,3v/8)
5 (u,v/4)
6 (u,v/8)

1

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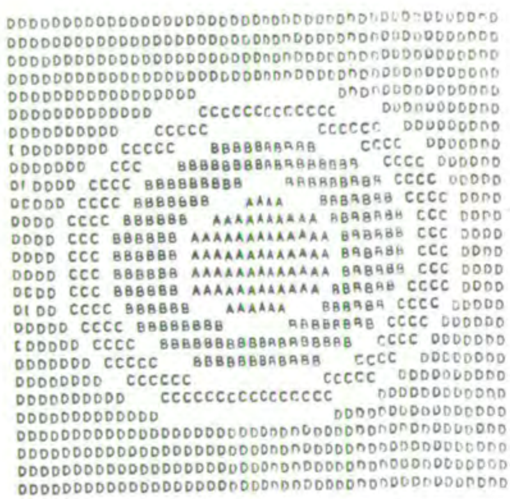

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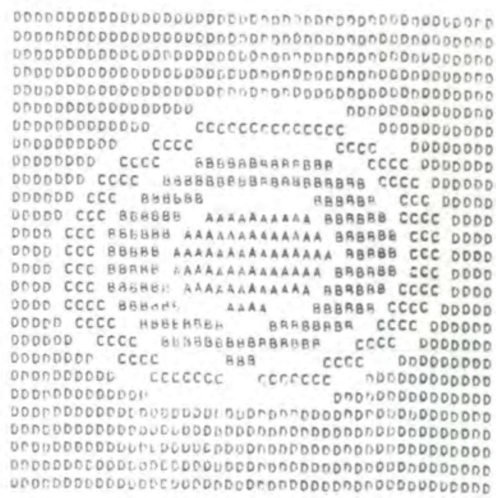

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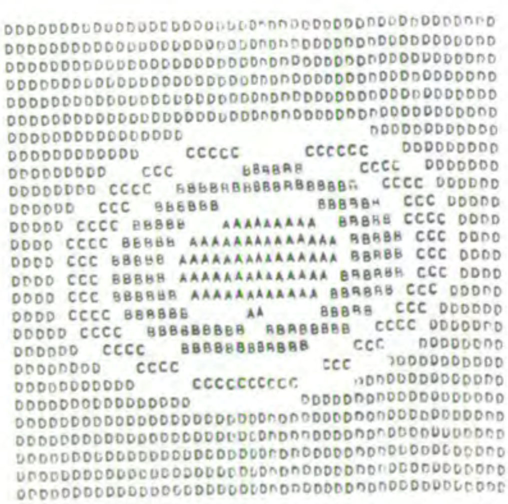

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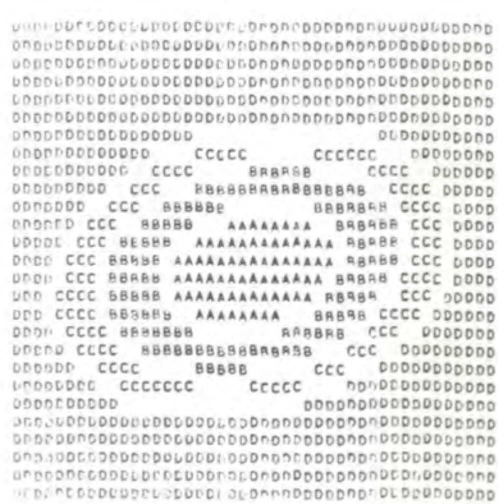


6

Data set	Taxonomic distance from surface to standard	Surface to standard correlation
(u,v)	0.000	1.000
(u,3v/4)	0.278	0.993
(u,v/2)	1.616	0.983
(u,3v/8)	1.847	0.963
(u,v/4)	3.559	0.939
(u,v/8)	5.619	0.913

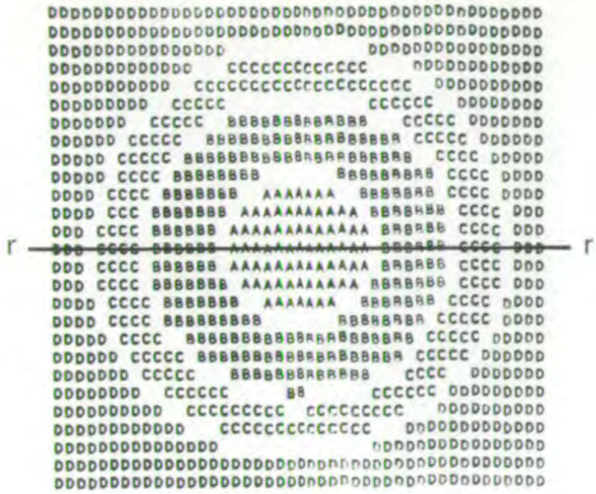
Table(5.3.5) Test 1 ; comparison of apparent trend surfaces to the standard.

Data set	Co-ordinate correlation within control area	Co-ordinate correlation within map area
(u,v)	0.112	0.140
(u,3v/8)	0.109	0.396
(u,v/2)	0.094	0.681
(u,3v/8)	0.115	0.808
(u,v/4)	0.126	0.905
(u,v/8)	0.114	0.976

Table(5.3.6) Test 1 ; linearity of the control distribution.

Figure(5.3.7) Progressive distortion of a quadratic trend surface under the increasing influence of Type 2 linearity. Linearity created by reduction of the 'v' co-ordinate (orthogonal to the reduced major axis (r) which is the (u) axis) for all but 15 points in the distribution.

1 (u,v)
2 (u,3v/4)
3 (u,v/2)
4 (u,3v/8)
5 (u,v/4)
6 (u,v/8)



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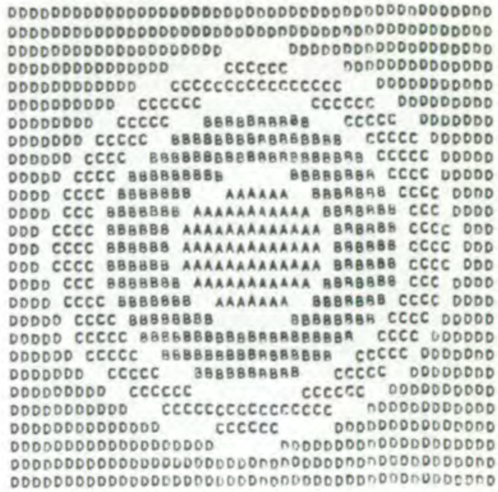

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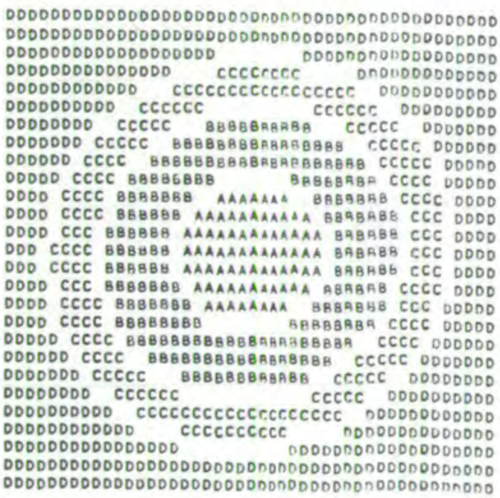

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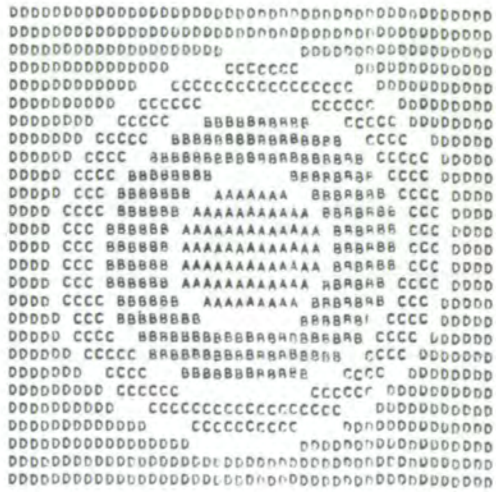

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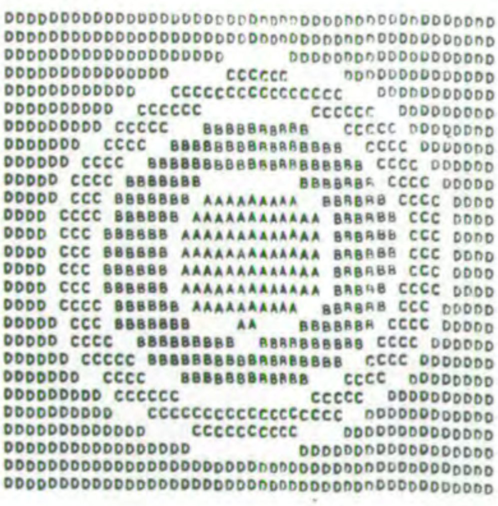

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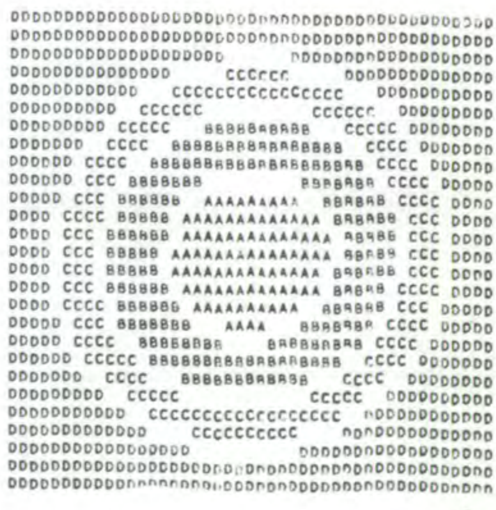


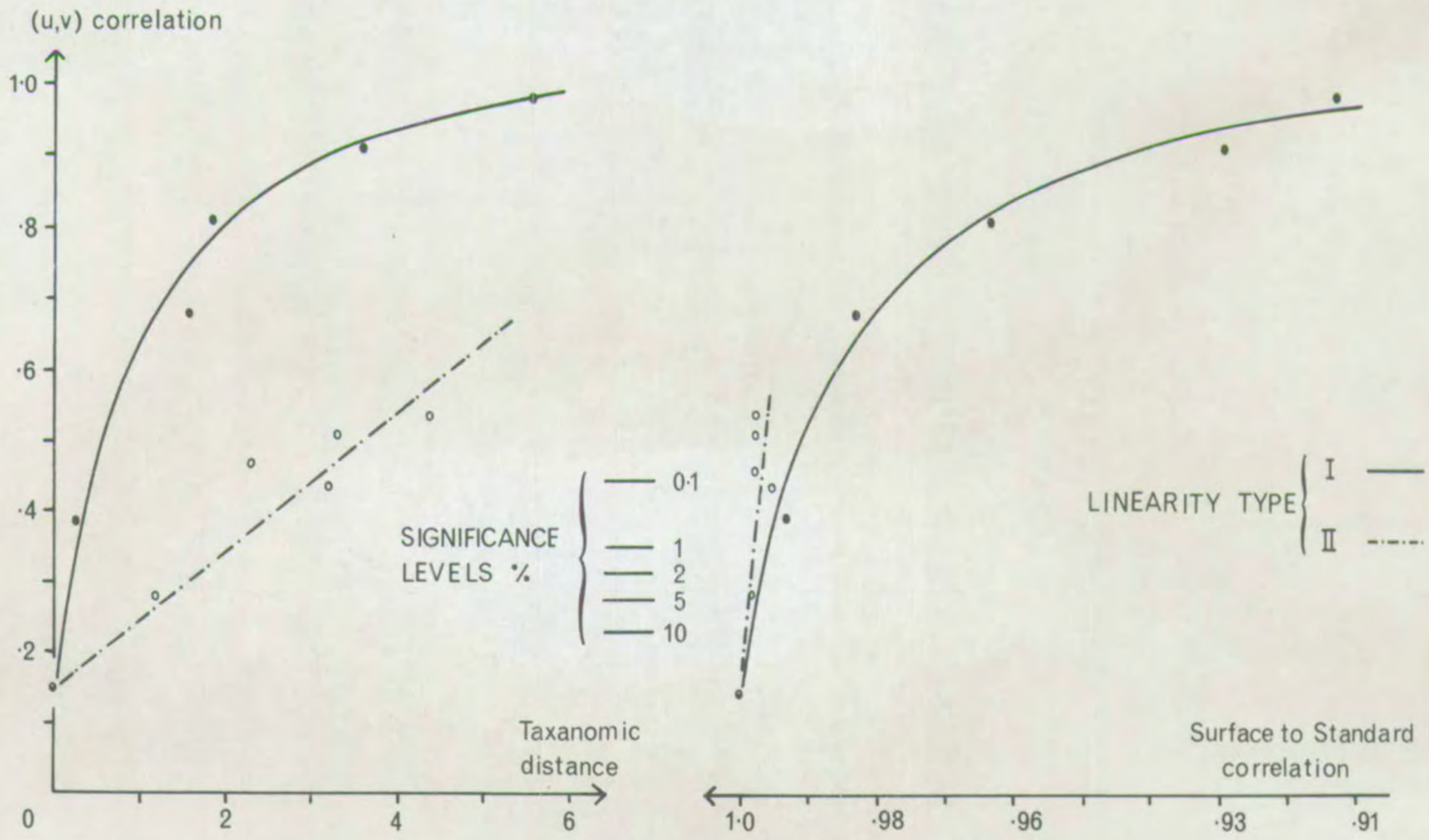
6

Data set	Taxonomic distance from surface to standard	Surface to standard correlation
(u,v)	0.000	1.000
(u,3v/4)	1.186	0.999
(u,v/2)	3.229	0.998
(u,3v/8)	2.311	0.999
(u,v/4)	3.357	0.999
(u,v/8)	4.396	0.999

Table(5.3.8) Test 2 ; comparison of trend surfaces to the standard.

Data set	Co-ordinate correlation within control area	Co-ordinate correlation within map area
(u,v)	0.116	0.140
(u,3v/4)	0.236	0.238
(u,v/2)	0.355	0.419
(u,3v/8)	0.435	0.474
(u,v/4)	0.475	0.510
(u,v/8)	0.555	0.538

Table(5.3.9) Test 2 ; linearity of control distribution.



Figure(5.3.10) The relationship between surface distortion and data linearity.

done to non-artificial surfaces, because there is no accurate way of assessing the amount of distortion as against the contribution of any <u>real</u> trend.

However, this result can be used as a guide to the potential distortion arising from similar distributions. A quantitative measure of distortion, the taxonomic distance from the standard, is shown in table (5.3.5). The trend surfaces produced under the influence of Type 2 linearity are shown in figure (5.3.7), taxonomic distances in table (5.3.8) and distribution correlation coefficients in table (5.3.9).

A visual comparison shows that Type 1 linearity produces pronounced distortion while that arising from Type 2 is slight. The plot of taxonomic distance against distribution correlation brings out this result, figure (5.3.10), although the curves are not directly comparable because the taxonomic distance is only a relative measure of similarity. However, after an initial slow rise, the rate of increasing distortion is greater for Type 1 than Type 2.

Direct comparison can be obtained from surface to surface correlations which in this case were based on a rectangular grid of 49 points; figure (5.3.10). The results, consistent with those derived from the use of the taxonomic distance, should be treated with care for the reasons discussed previously.

5.3 (b) Test 2

The objective of this second simulation was to extend the results obtained above. Data was computed for artificial and geological distributions, using the known coefficients of a cubic trend surface (the standard). Linear, quadratic and cubic surfaces were computed from this data.

The first six runs were designed to measure the effect of changing the number of sample localities (from 48 to 20) and their distribution from gridded, to even but not gridded, to random. The distributions and resulting surfaces are shown in figures (5.3.12) and (5.3.13), and should be compared with the standard shown in figure (5.3.11).

Only very slight changes are apparent and these would not have any practical significance. The close similarities are brought out by the very small taxonomic distances from the standard, a result which perhaps could have been predicted from the insignificant correlations amongst the control points; table (5.3.23).

Nine further runs were made to measure the potential distorting effects of some common geological sampling schemes.

The 'clusters' distribution consists of three restricted groups of fifteen points and, since the control area is a good approximation to the map area, there is no contribution from Type 1 linearity. The recomputed linear and quadratic surfaces are virtually identical to the standard while the cubic is only slightly distorted; figure (5.3.14). In all cases the surfaces have been shifted slightly vertically due to a change in the mean of the raw data.

The 'one cluster' distribution is uniform within the control area but extremely grouped with respect to the map. The quadratic and cubic surfaces are greatly distorted because the turning points are restricted to the control area; figure (5.3.15). The linear trend is only slightly steeper than the standard but the similarity is probably fortuitous.

The 'outcrop' distribution has a significant correlation coefficient, table (5.3.23), which arises only from Type 2 linearity. The linear and cubic surfaces are very similar to the standard but the quadratic is distorted, particularly in areas of weak control; figure (5.3.16). The same result was obtained from the 'reversed outcrop' distribution, which was designed to measure the effect of the position of the restricted control belt; figure (5.3.17).

Poor quadratic and good cubic reproduction can possibly both be explained by reference to the structure of the data (a pure cubic trend). Presented to the quadratic computation, the data consists of two components, regional and local, since its complexity cannot be taken up by a second degree polynomial. Presented to the cubic computation it consists of only one component. In the first case the data is, therefore, noisy and in the second noiseless.

The 'outcrop and bore' distribution was produced by adding a grid of 12 points, representing boreholes, to the 'outcrop' pattern. Figure (5.3.18) shows that while the correlation coefficient remains significant the small amount of extra information causes almost exact reproduction of the standard in every case.

The apparently highly skewed 'traverse' distribution contains principally Type 2 linearity and the trend surfaces only differ from the standard in having slightly steeper slopes; figure (5.3.19).

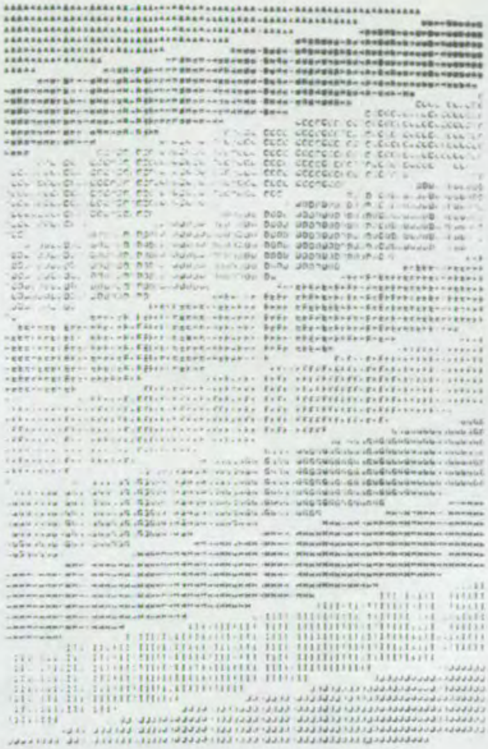
Extreme Type 1 linearity in the 'diagonal' distribution gives rise to quadratic and cubic surfaces with shapes entirely controlled by the pattern of observation points. These surfaces are totally unlike each other as well as the standard. The linear surface is rotated and steepened compared to the standard but has the same overall sense; figure (5.3.20).

Although the correlation remains high the emphasis is partly shifted from Type 1 to Type 2 linearity in the 'diagonal + 1' pattern, with a corresponding marked increase in the similarity to the standard; figure (5.3.21). Like 'outcrop and bore' much better results can be obtained with the addition of a minimal amount of extra information (in this case just 3 points).

A further 3 points were added to produce the 'diagonal + 2' distribution, in which the linearity is entirely Type 2, again with a concomitant increase in the accuracy of the simulation; figure (5.3.22). The cubic surface remains appreciably distorted, probably because of the tendency for the turning points to be located near areas of greater control density.

The results of this series of experiments are summarised in table (5.3.23) in terms of taxonomic distances and correlation coefficients.

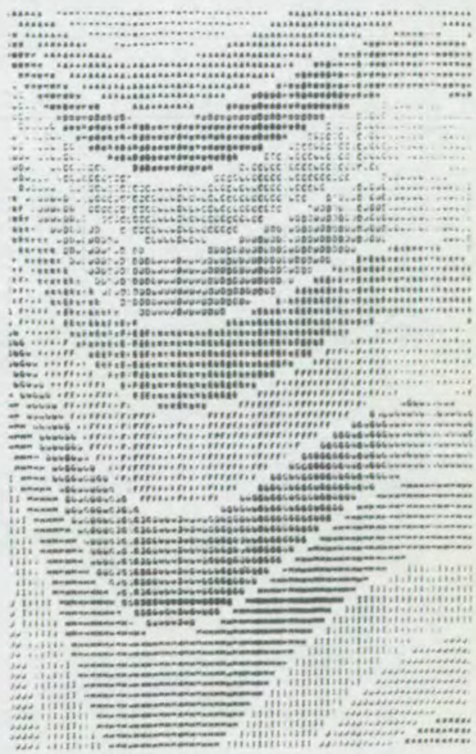
Both artificial tests vindicate the technique of trend analysis. The method does fail under the influence of Type 1 linearity, but can produce apparent trends practically identical to their real counterparts under fairly extreme Type 2 linearity, or where the data is clustered provided that the control area is coincident with the map. Distortions due to these effects will be greater where the data is noisy.



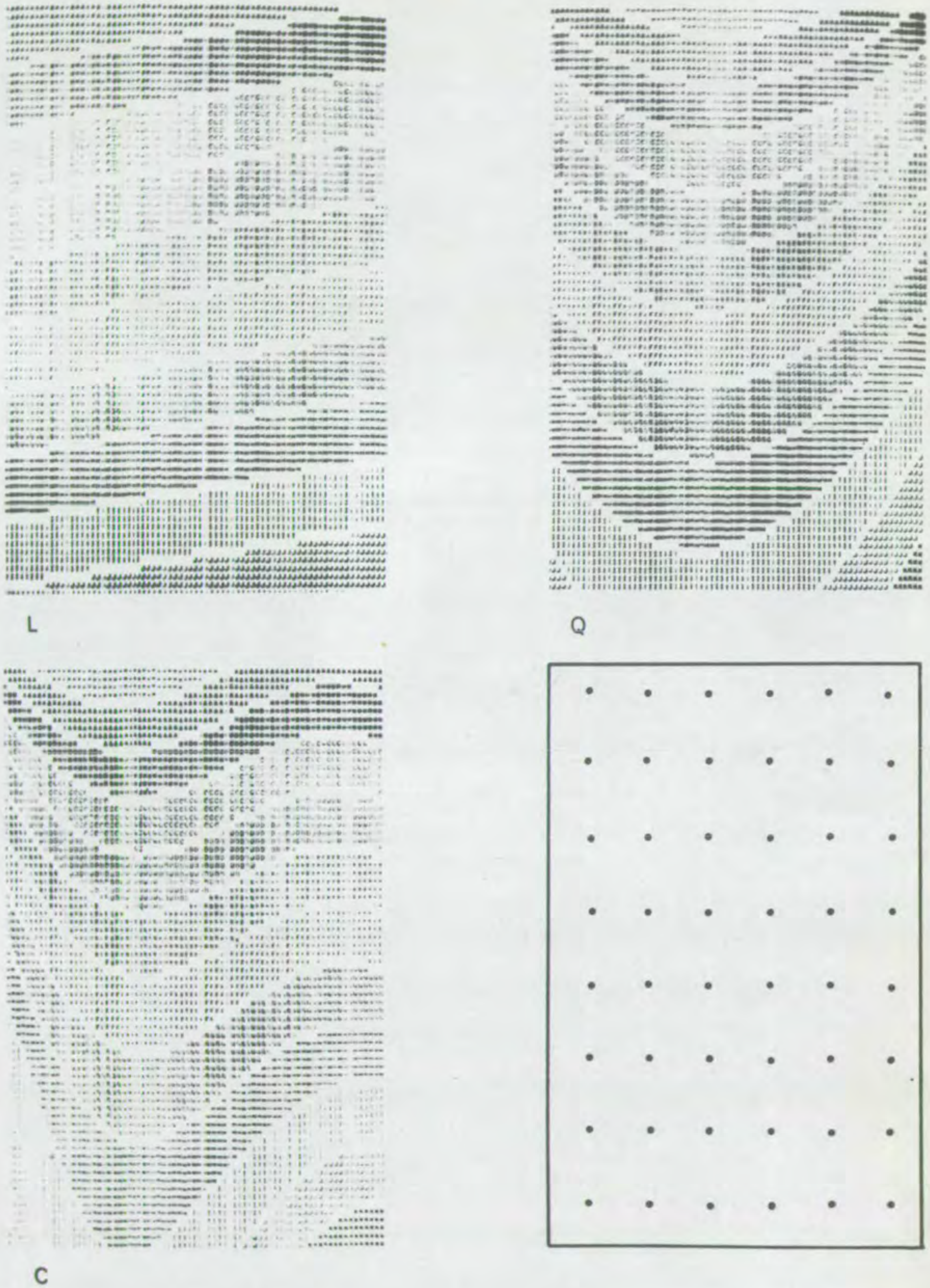
L

Q

Figure(5.3.11) The standard cubic trend surface (C) plus linear (L) and quadratic (Q) components.



C

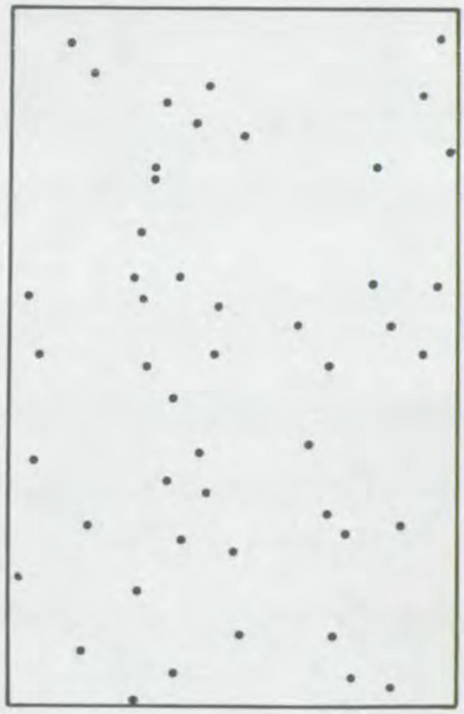


Figure(5.3.12a) 48 points, even distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.

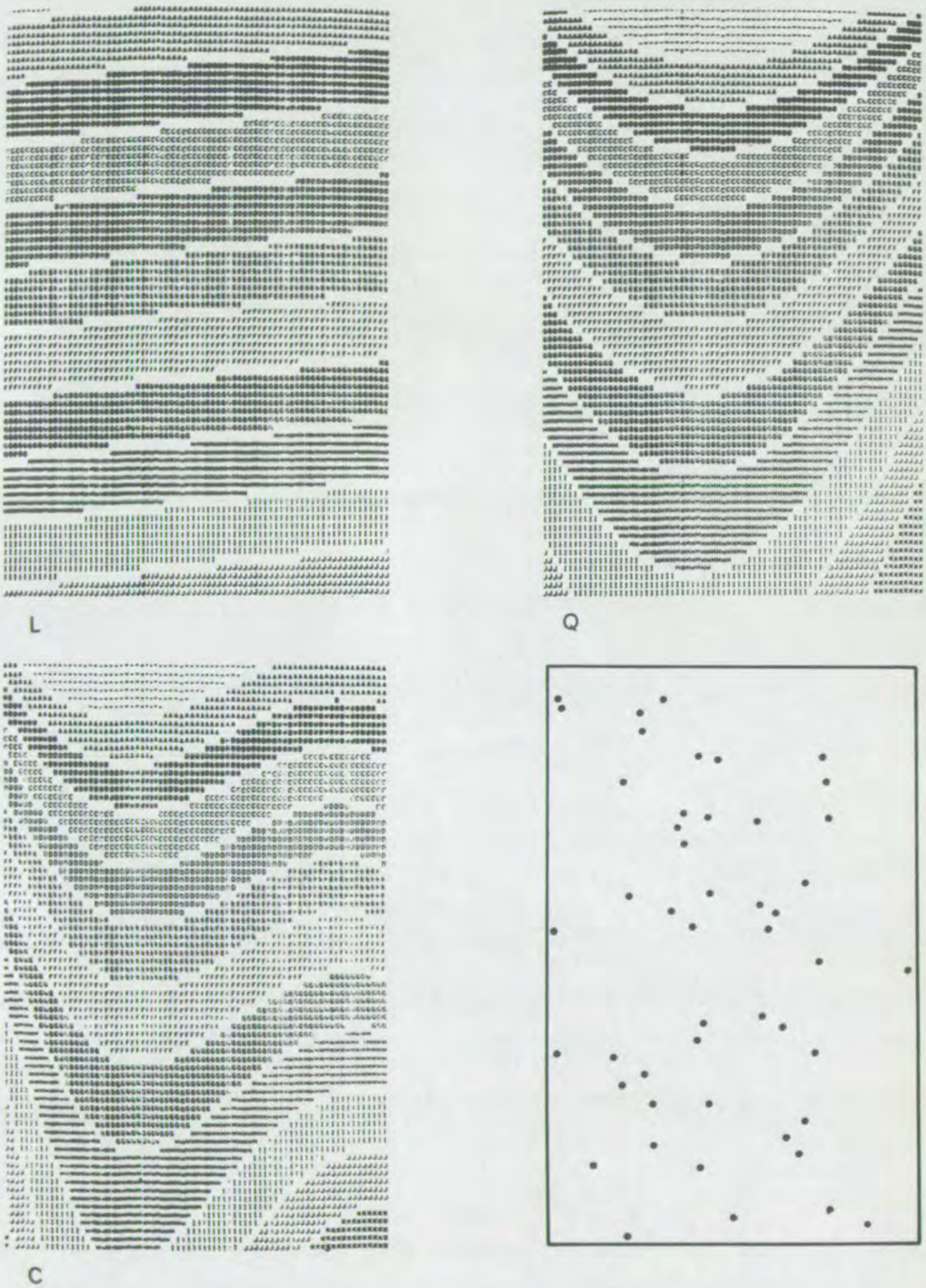
L

Q

C



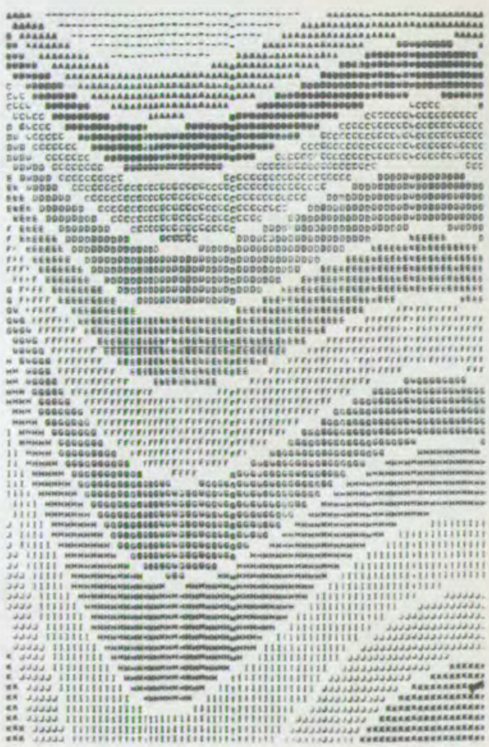
Figure(5.3.12b) 48 points, even distribution not gridded. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



Figure(5.3.12c) 48 points, random distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.

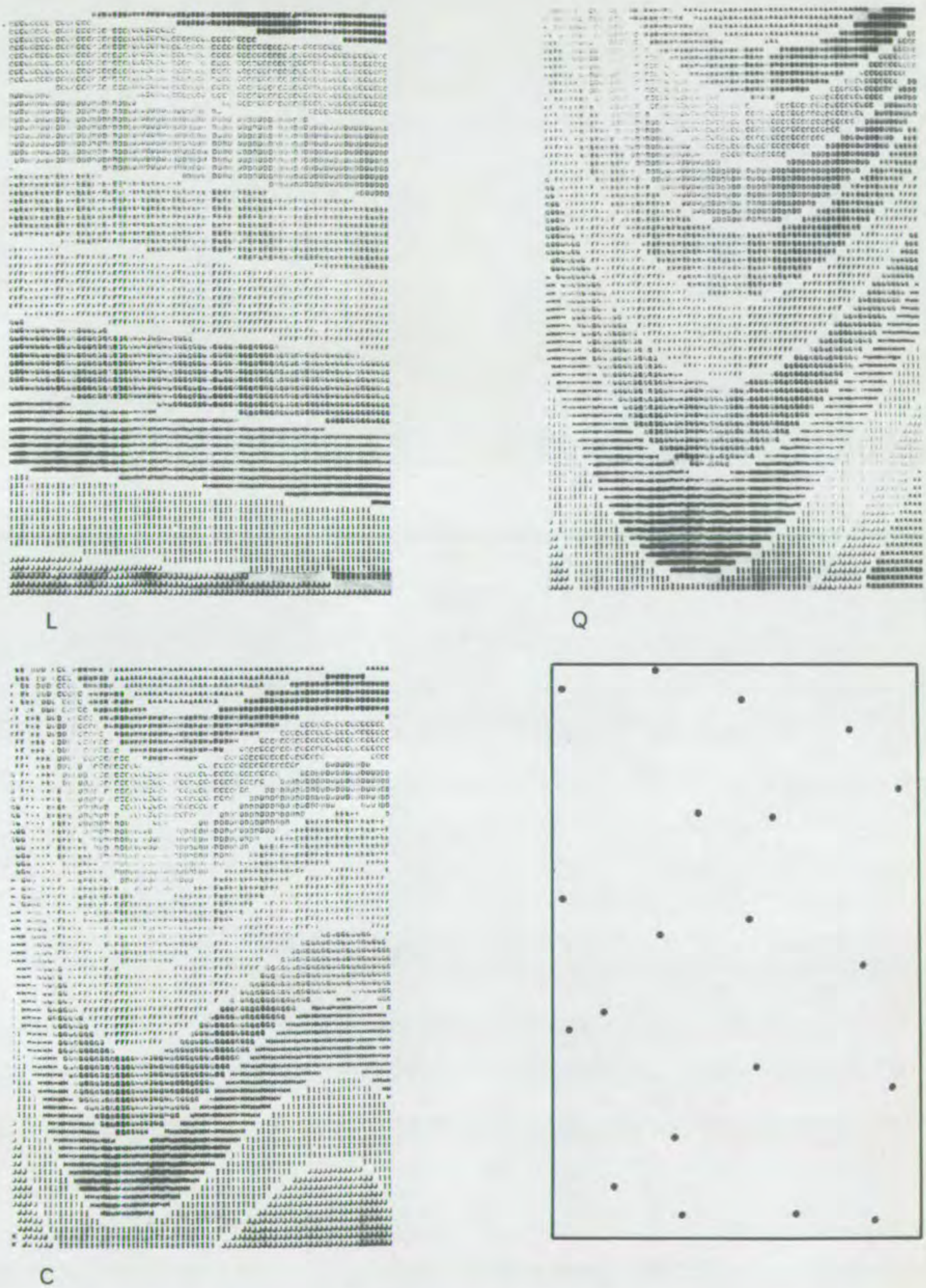
L

Q

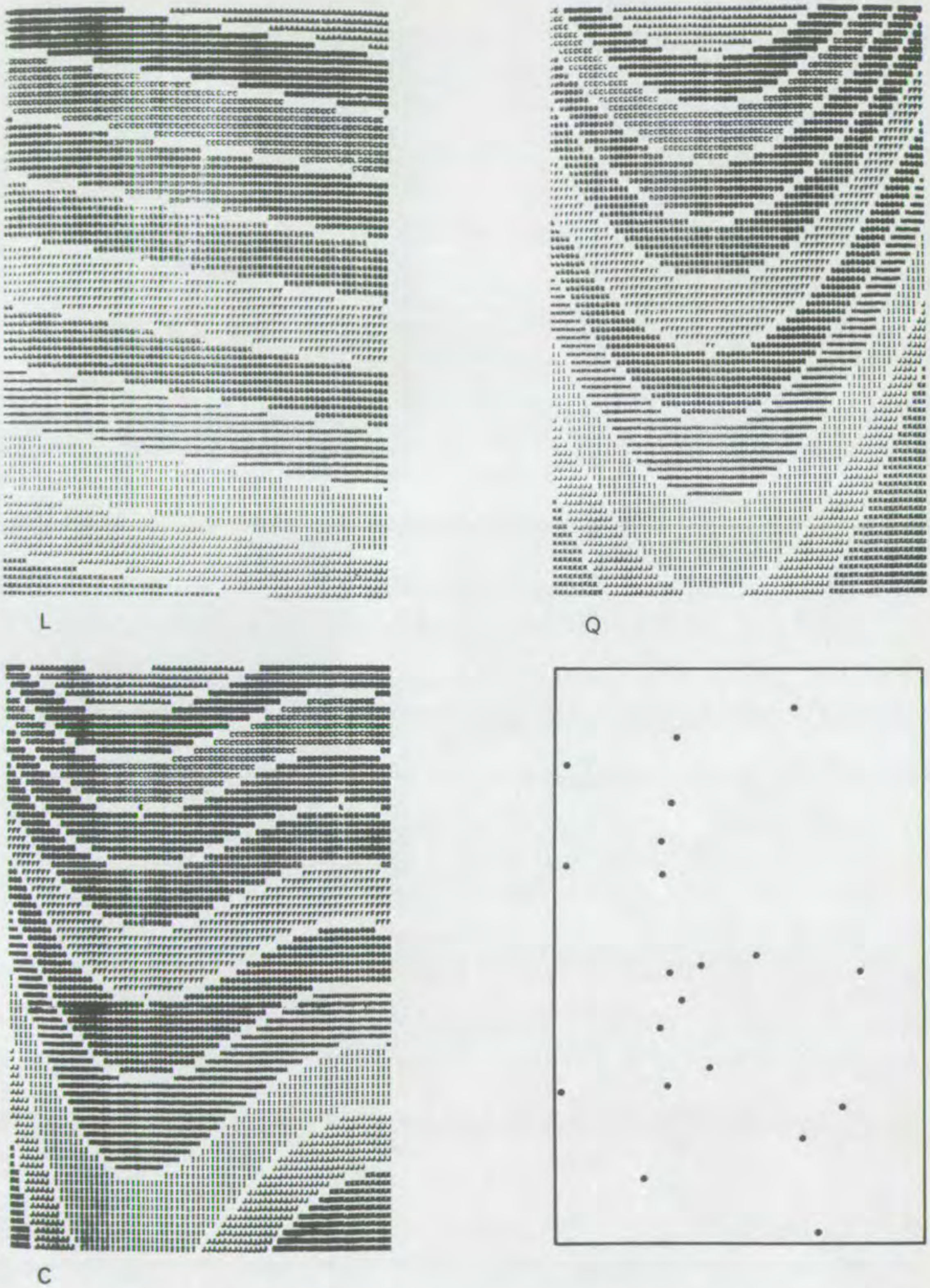


C

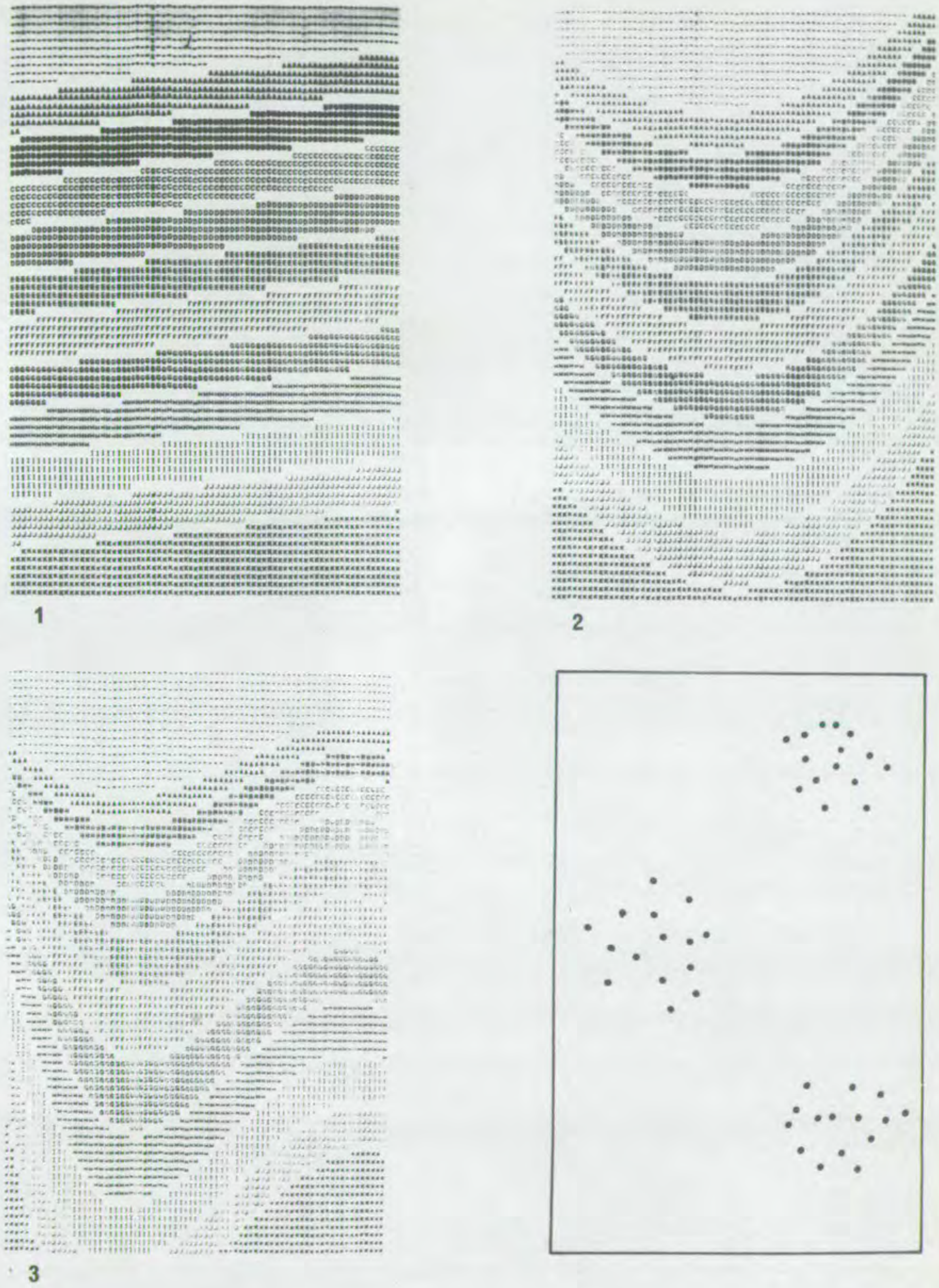
Figure(5.3.13a) 20 points, even distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



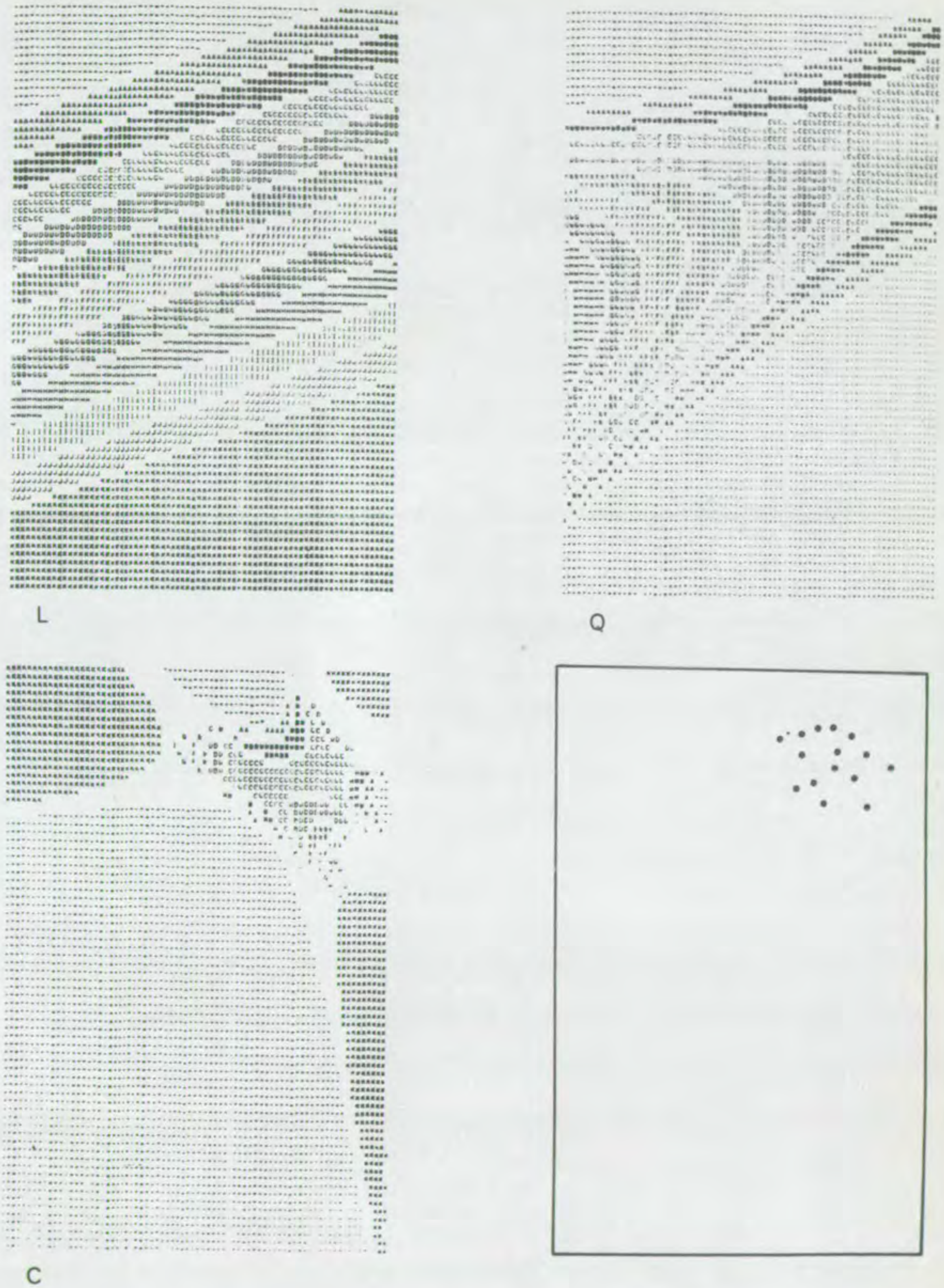
Figure(5.3.13b) 20 points, even distribution not gridded. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



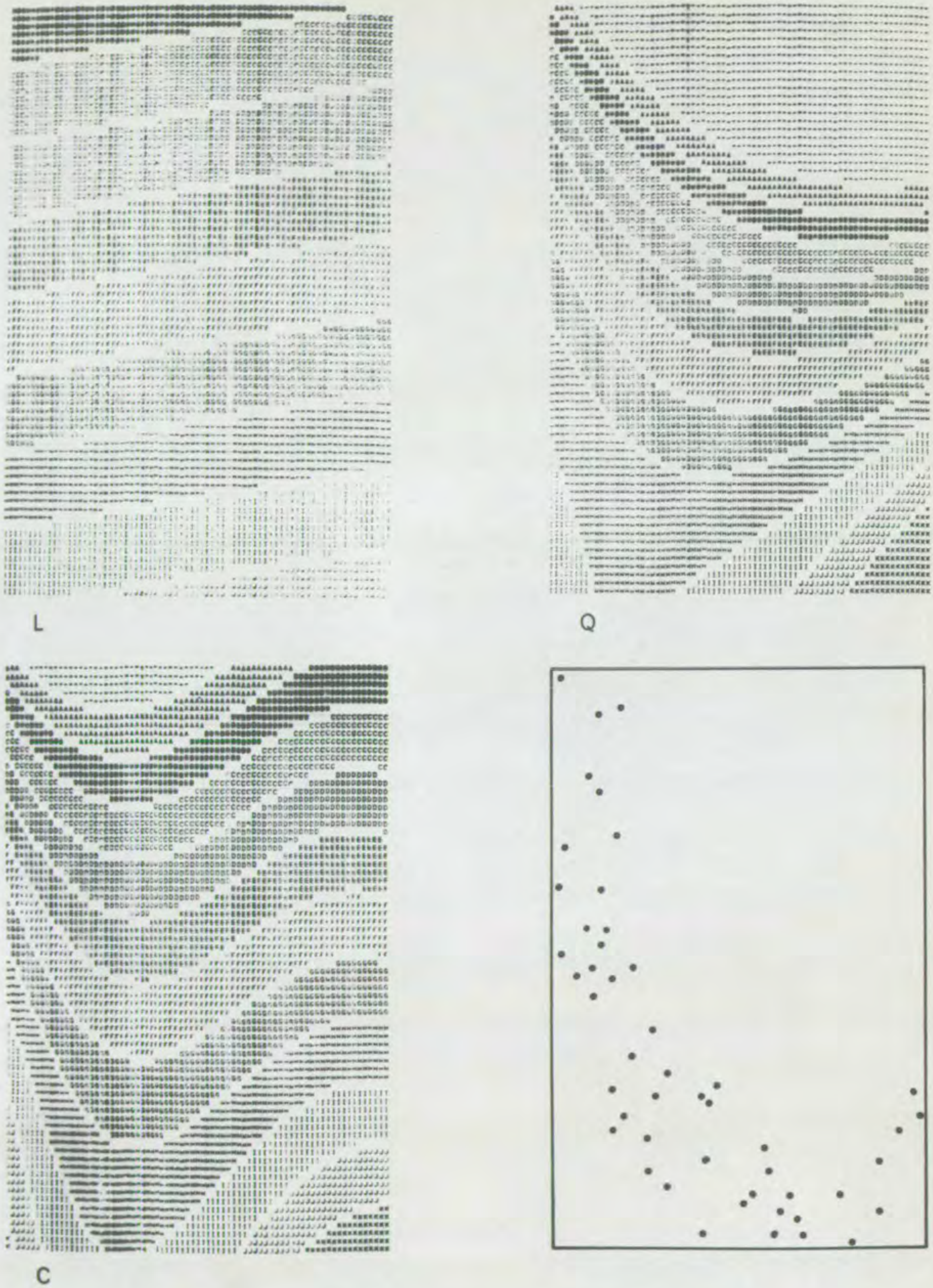
Figure(5.3.13c) 20 points, random distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



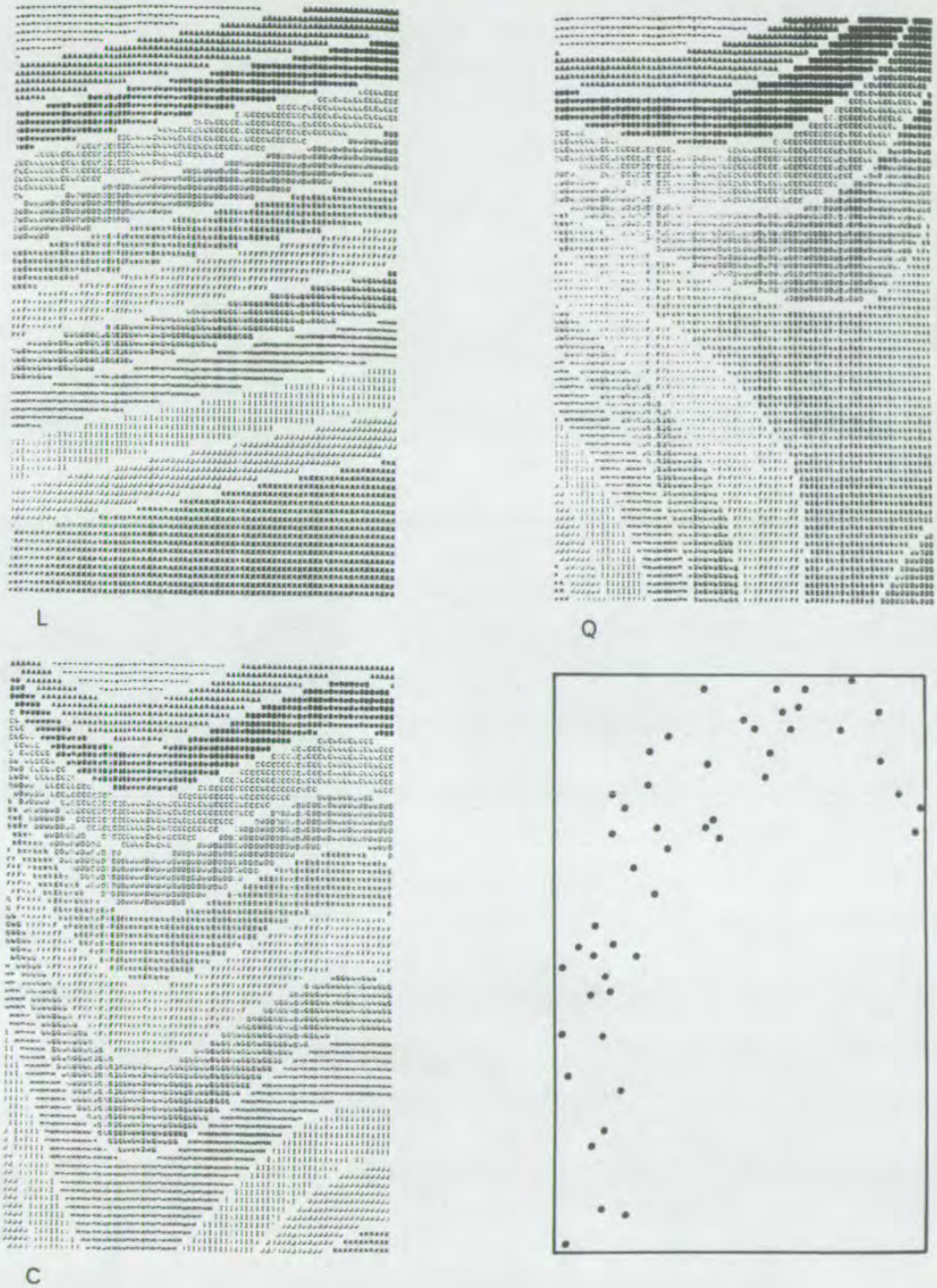
Figure(5.3.14) 45 points, 3 clusters. Linear (1), quadratic (2) and cubic (3) trend surfaces.



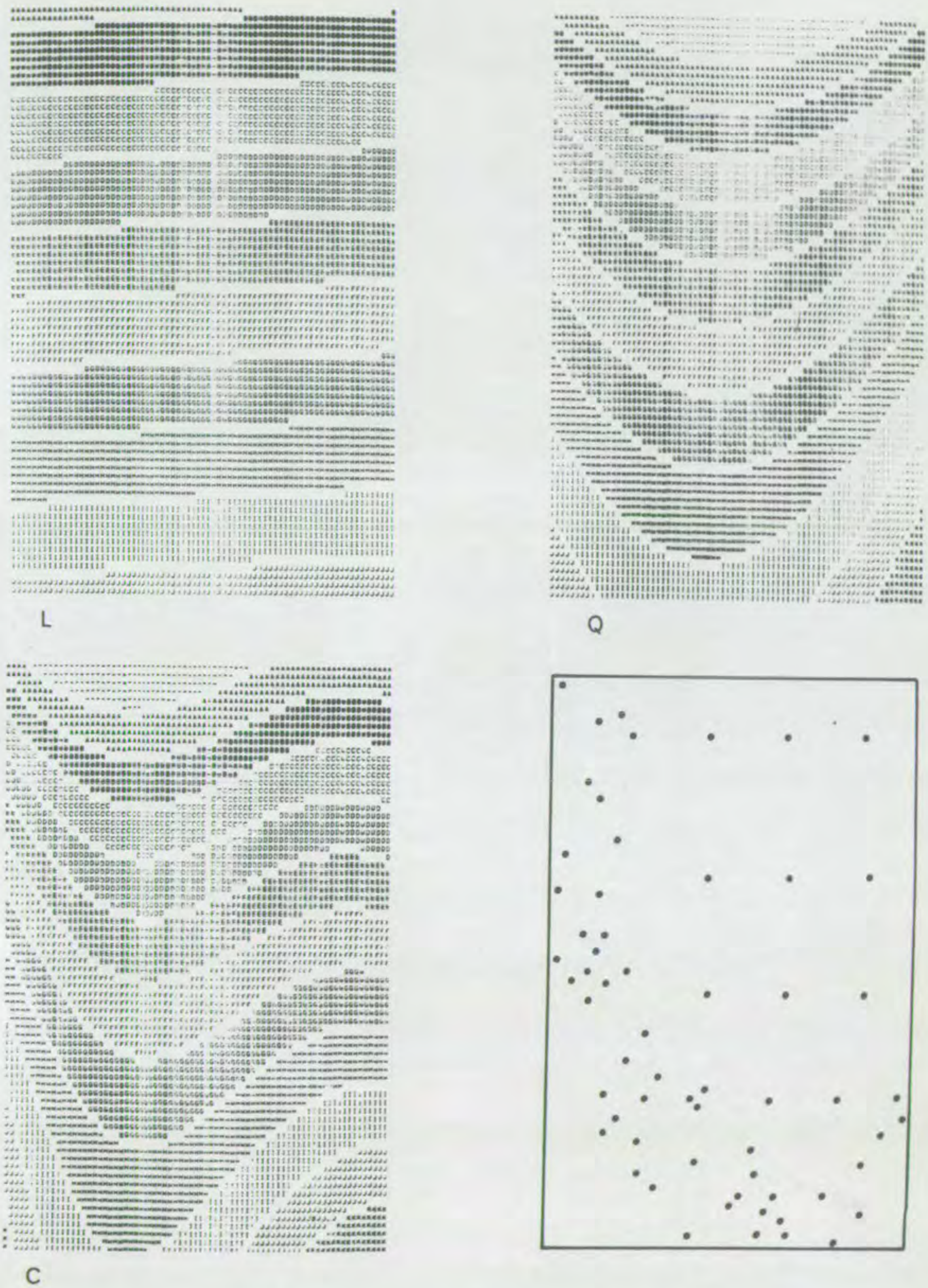
Figure(5.3.15) 15 points, 1 cluster. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



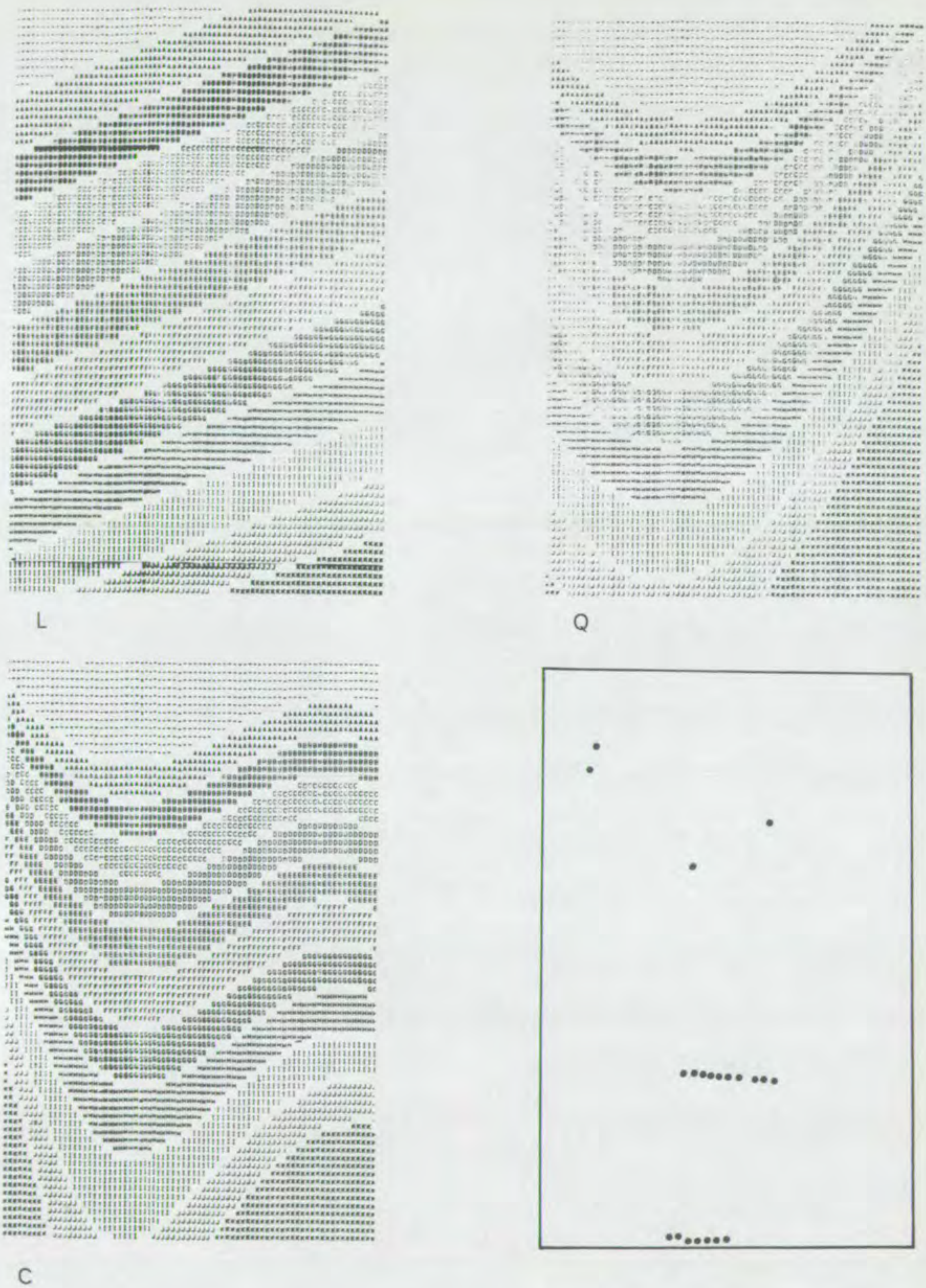
Figure(5.3.16) 49 points, outcrop distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



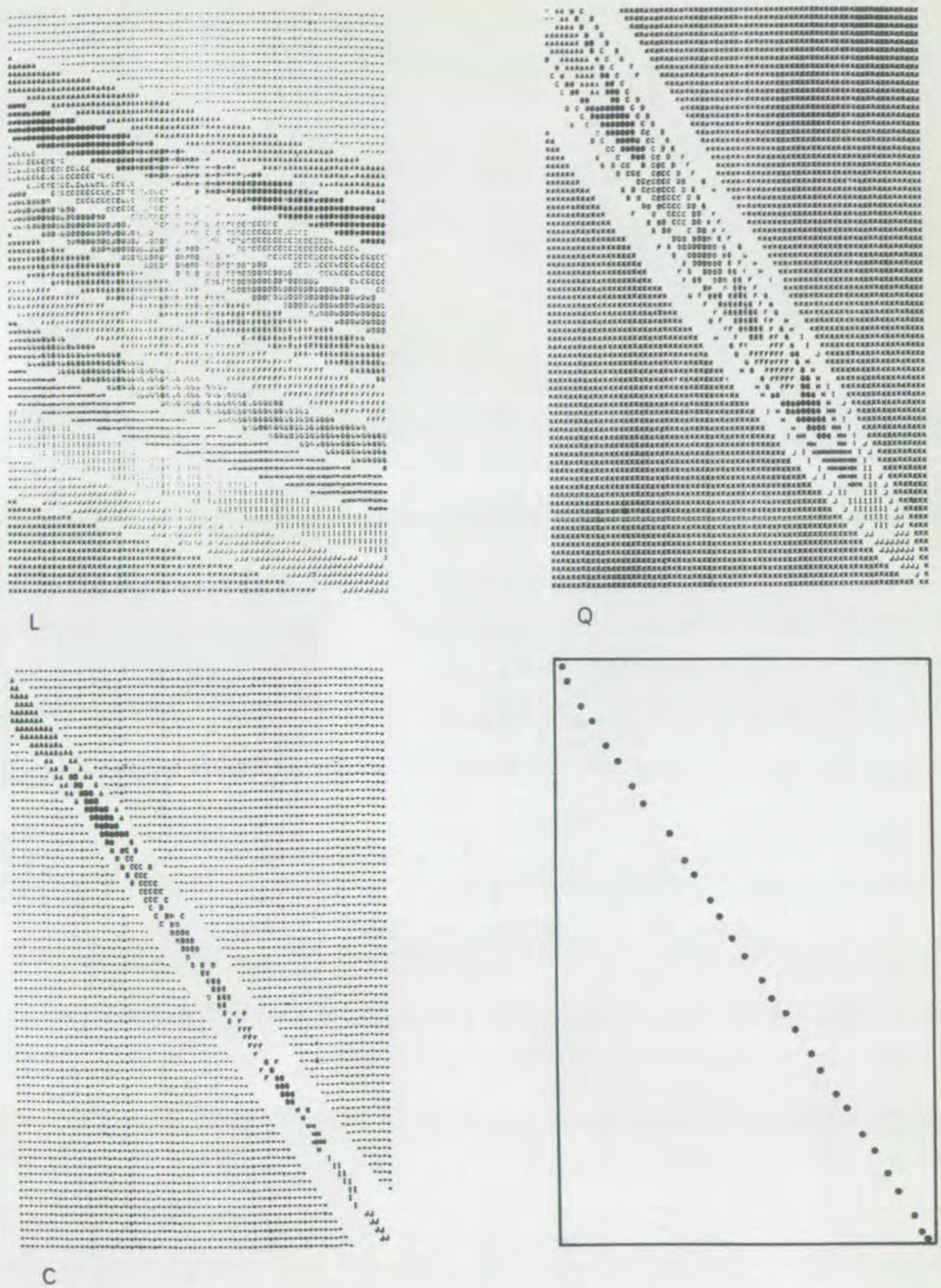
Figure(5.3.17) 49 points, reversed outcrop distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



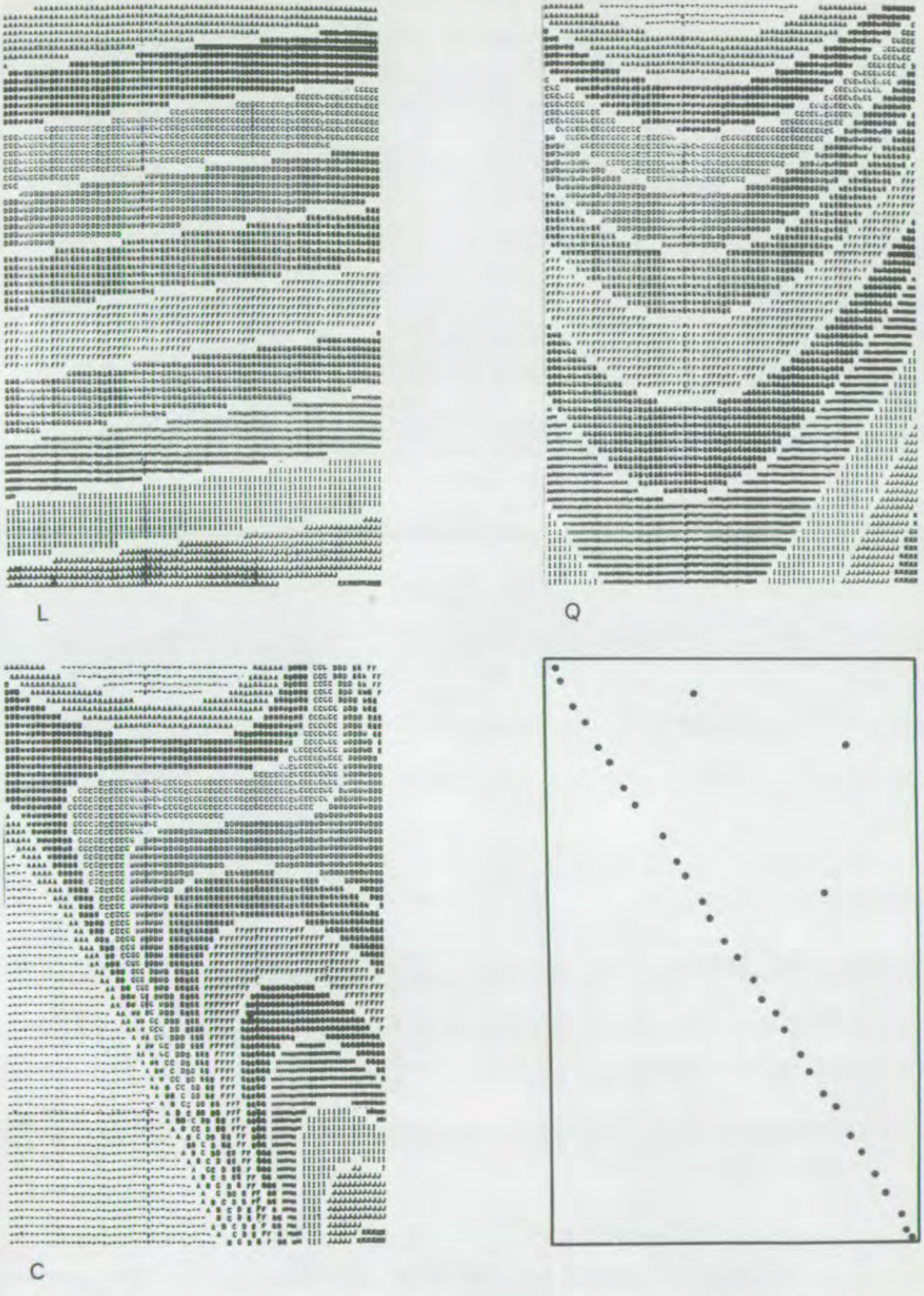
Figure(5.3.18) 61 points, outcrop and bore distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



Figure(5.3.19) 21 points, traverses distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



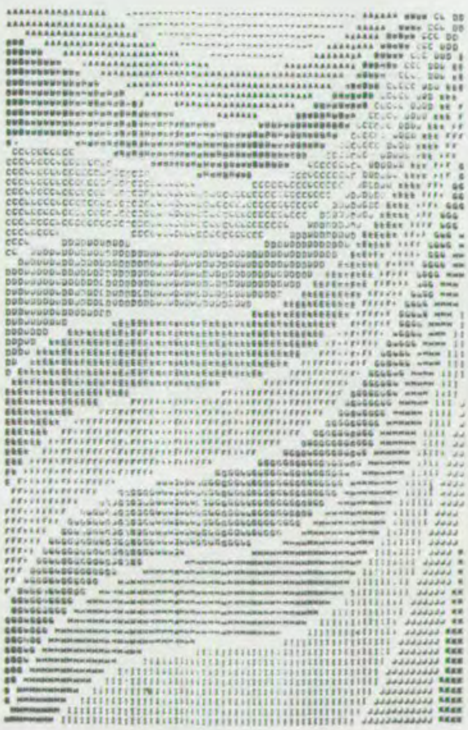
Figure(5.3.20) 30 points, diagonal distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.



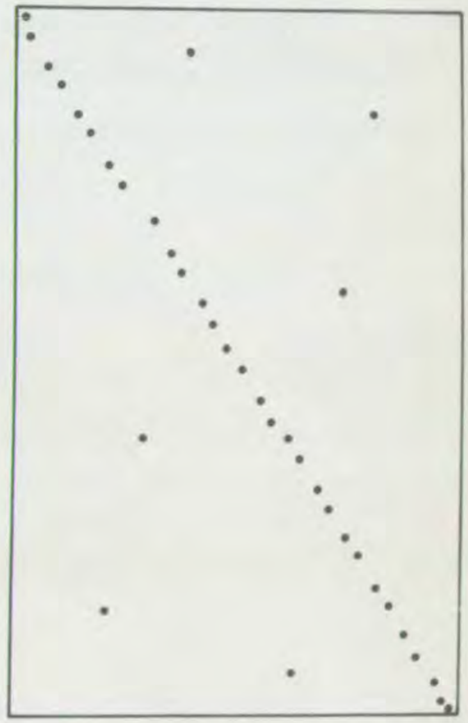
Figure(5.3.21) 33 points, diagonal plus 1 distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.

L

Q



C



Figure(5.3.22) 36 points, diagonal plus 2 distribution. Linear (L), quadratic (Q) and cubic (C) trend surfaces.

Table(5.3.23) Results from the second simulation test.

distribution	sample size	taxonomic distance. 10^{-2} linear	quadratic	cubic	distribution correlation	linearity type
even grid	112	0.000	0.000	0.000	+0.01	-
even grid	48	0.989	0.108	0.213	0.00	
even non-grid	48	3.807	42.330	3.615	+0.08	
random	48	9.678	19.660	0.213	-0.14	
even grid	20	7.001	1.047	0.233	0.00	
even non-grid	20	121.600	122.100	85.250	-0.06	
random	20	239.400	168.600	0.191	-0.19	
clusters	45	15.320	25.540	96.560	-0.05	2
one cluster	15	1848.333	346.728	751.697@@	-0.12	1
outcrop	49	104.400	681.900	2.816	-0.69£	2
reverse outcrop	49	658.300	361.900	0.085	-0.83£	2
outcrop and bore	61	31.030	10.270	0.239	-0.39£	2
diagonal	31	899.119	8862.523	696.373@	-0.90£	1
diagonal + 1	34	13.100	21.540	1095.000	-0.90£	1 (+2)
diagonal + 2	37	26.100	5.043	107.400	-0.80£	2
traverses	21	110.200	50.370	0.190	-0.63£	2

@ = $.10^3$; @@ = $.10^6$; £ = significant at the 5 % level

These results can be reviewed within the context of the three critical requirements of any sample submitted to analysis, as listed by Krumbein (1960).

a) How many points are required for a satisfactory map?

b) How evenly should the points be distributed over the map?

c) How wide need the map strip be in relation to its length?

The answer to the first point depends upon the purposes for which the map is constructed. However, minimum requirements for interpretive purposes are probably appreciably larger than in common use at the moment. Where control and map areas are coincident, undistorted maps can probably be produced from heavily clustered data, and the ratio of map width to length will have no statistical effect.

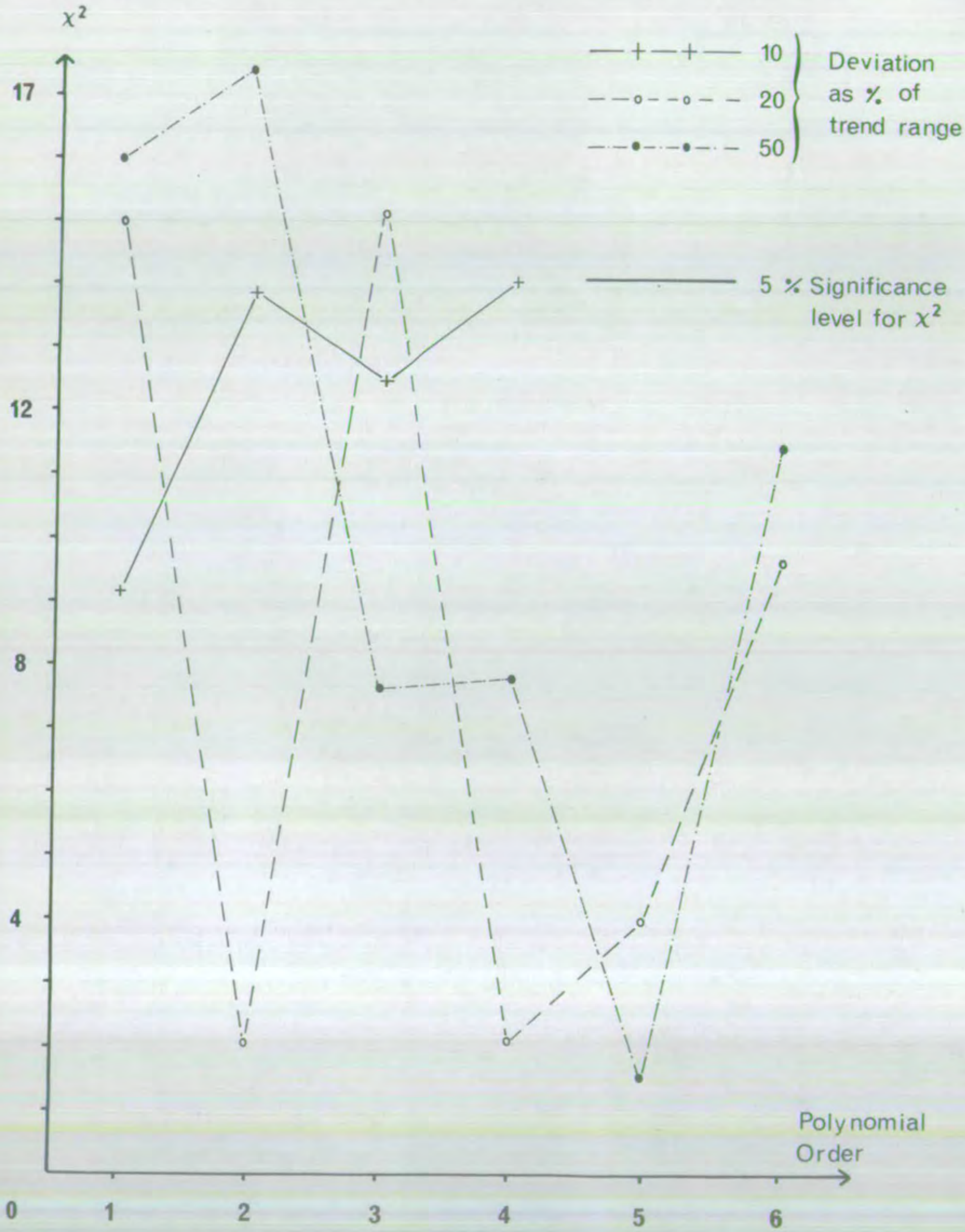
5.4 Interpretation

Given a sufficient quantity of unbiased data the problem still remains of selecting the desired trend surface. Which of the many available methods is used depends upon the purpose for which the surface has been constructed. Where the requirement is an equation which simply describes a trend, increasingly complex polynomials can be computed until the prediction is economically acceptable. However, to make geological sense from areally distributed information it is usually necessary to separate it into its component parts and to estimate their magnitude and extent.

Selection for these more exacting purposes can be attempted from a subjective or geological standpoint. Arbitrary selection on some predetermined basis, the 'ad hoc' method of Allen and Krumbein (1962), or the technique of secondary trend components (Allen and Krumbein 1962, Whitten 1963) are amongst the most effective. The use of confidence intervals requires the assumptions that the deviations are uncorrelated and are normally distributed with a zero mean. It is most unlikely that low order surfaces could even meet these maximum likelihood requirements, and yet the maps of confidence intervals of even quadratic surfaces are very complex (Krumbein and Graybill 1965) and probably of no interpretive value. Furthermore, it seems probable that the nature of the confidence intervals is partly dependent upon the control distribution.

Statistical techniques of trend selection include testing the polynomial coefficients for redundancy (Krumbein 1966), a study of the frequency distribution of residuals (Grant 1957, McIntyre 1967) and the comparison of explained and unexplained variance with increasing polynomial order.

Little can be said about the first method except that it is possibly more philosophically intriguing than practically applicable. The study of the frequency distribution of deviations is, however, a poor technique. Theoretically, if the deviations are random and uncorrelated they should be normally distributed; however, it is unlikely that a balance, between mean area, extent of local processes and polynomial flexibility, could ever arise so as to separate out the purely residual components. The chance inclusion of local effects, arising through the



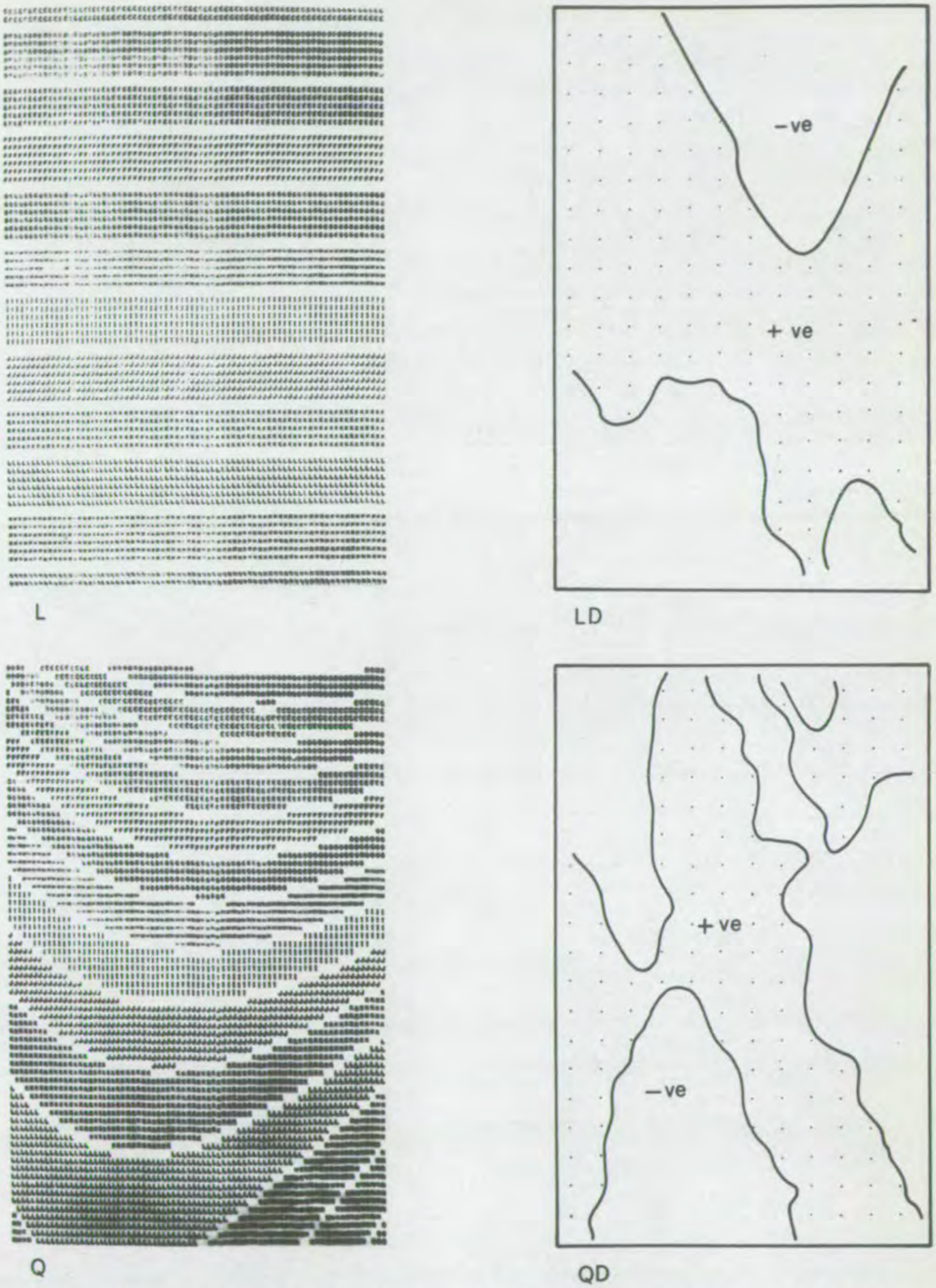
Figure(5.4.1) The normality of trend surface deviations.

use of least squares techniques, must inevitably give rise to unpredictable departures from normality.

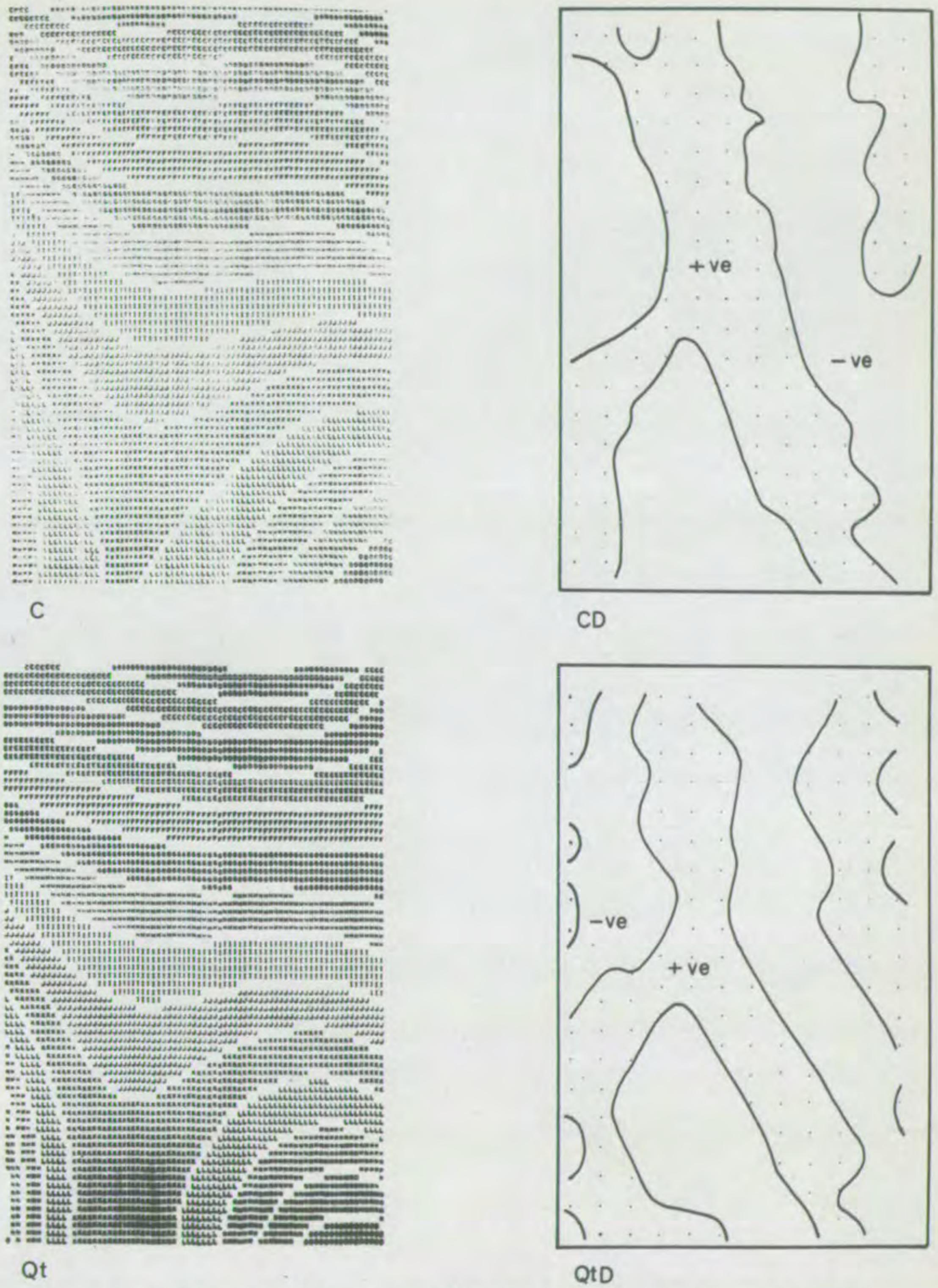
These conclusions were tested by an artificial simulation test in which a fixed local pattern of deviations, with a magnitude range of 10%, 20% and 50% of the trend, was added to the cubic surface used previously as a standard. The results which show the departure of the deviations from normality using the chi-square statistic, figure (5.4.1), speak for themselves. For example, the large decrease in the computed chi-square value, for cubic to quartic deviations for the trend plus 20% data set, implies that the latter has absorbed all the local and regional components. However, the difference in trend and deviation patterns from cubic to quartic are negligible, figure (5.4.2), and the quartic deviations clearly contain local components.

The fit, or percent sum of squares of the raw data explained by the polynomial, is the most commonly employed criterion for choosing trend surfaces. However, the fit takes no account of possible distortions of the apparent trend surface. For example, all the fits of the surfaces of the second artificial test were very high, table (5.4.3); even linear surfaces, in this case totally unlike the regional process, managed to explain almost all the variance. The cause appears to lie in the structure of the raw data. Where the noise level is low, fits will tend to be high regardless of the accuracy of the trend in describing regional variations. Conversely, where the noise level is high, the fit will be small however accurate the simulation of the regional component by the trend surface.

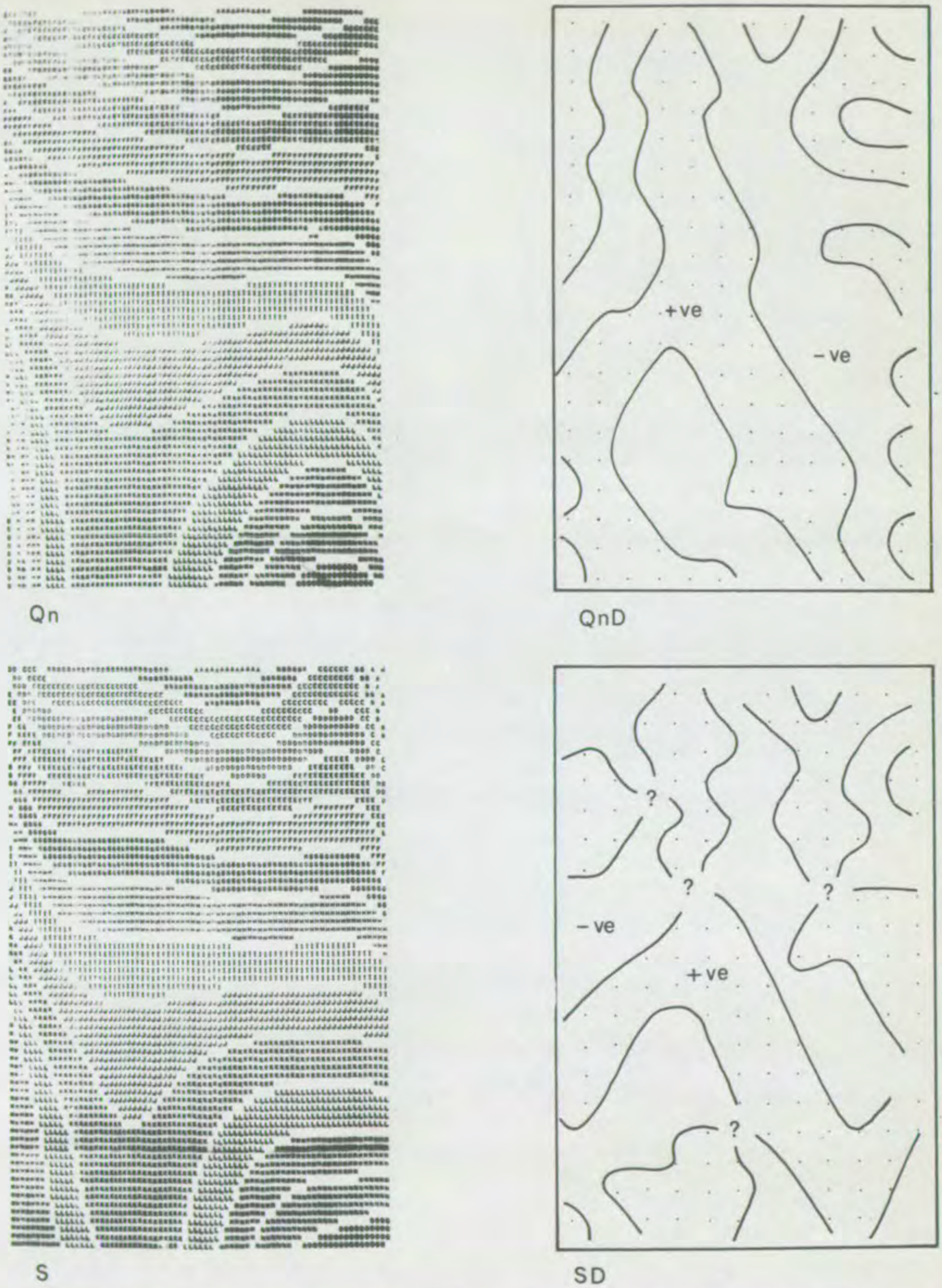
Disregarding the absolute values, the increase in fit of one



Figure(5.4.2a) Trend plus 20% deviation. Linear (L) and quadratic (Q) trend surfaces, plus their deviations (LD, QD).



Figure(5.4.2b) Trend plus 20% deviation. Cubic (C) and Quartic (Qt) trend surfaces, plus their deviations (CD, QtD).



Figure(5.4.2c) Trend plus 20% deviation. Quintic (Qn) and sextic (S) trend surfaces, plus their deviations (QnD, SD).

Distribution	N	% Sum of squares explained Linear	Quadratic	Cubic
Even grid	112	94.8	98.7	99.9
Even grid	48	95.6	99.0	100.0
Even non-grid	48	92.5	98.5	99.8
Random	48	94.1	98.6	100.0
Even grid	20	96.6	99.4	100.0
Even non-grid	20	83.9	96.3	98.7
Random	20	92.0	99.2	100.0
Clusters	45	97.0	98.7	99.2
One cluster	15	78.4	83.6	94.9
Outcrop	49	89.2	99.8	99.9
Reversed outcrop	49	98.1	99.7	100.0
Outcrop and Bore	61	91.2	98.3	99.9
Traverse	21	99.2	99.9	100.0
Diagonal	31	98.9	99.8	99.9
Diagonal plus 1	34	98.8	99.9	99.9
Diagonal plus 2	37	98.6	99.8	99.9

Table(5.4.3) Apparent fits of the surfaces computed as part of the second artificial test.

N number of points

surface over another has sometimes been used to select significant trends. This may be done empirically, or statistically using the analysis of variance as described by Krumbein and Graybill (1965). The method is outlined in table (5.4.4) but can be generalised by the equation for the pure component shown in table (5.4.5). From this equation it can be seen that the significance of a pure component of any order is assessed not only from the increase in fit over its predecessor but also from the absolute amount of explained variance. Thus, while a small increase may suggest non-acceptance of a surface where absolute values are low, this may not be true where they are high. The empirical method is, therefore, totally unreliable.

Unfortunately the statistical method, of comparison of the F ratio to standard tables, must also be rejected. Krumbein and Graybill (1965 p.337), amongst others, state that the basic assumption required for interpretation is that the deviations should not contain any systematic effects, and they only use the method to decide when to stop fitting higher order polynomials. However, this approach involves the new assumption that the increase in fit should fall off progressively as the polynomial order increases. This assumption is not justifiable in the light of experience, as demonstrated by four results from the East Midlands Coalfield; figure (5.4.6). Analysis of variance, applied to the three complete curves, shows that in each case when the method indicates that no higher order polynomial need be extracted, it is totally misleading; table (5.4.7). Unless surfaces are computed until the number of polynomial coefficients is only one less than the number of observations, this factor cannot be ignored.

Source of variance	Sum of squares	Degrees of freedom
due to linear surface	L	2
deviations from linear	T-L	(n-1)-2
due to linear plus quadratic	LQ	
due to quadratic alone	LQ-L	3
deviations from quadratic	(T-L)-(LQ-L)	(n-1-2)-3
due to linear, quad. & cubic	LQC	
due to cubic alone	LQC-LQ	4
deviations from cubic	(T-L)-(LQ-L)-(LQC-LQ)	(n-1-2-3)-4
etc.	etc.	etc.

where n= number of points used in computation : T = total sum of squares

a) Analysis of variance for quadratic surface (pure component)

$F(3, n-6) = ((LQ-L)/3)/(((T-L)-(LQ-L))/(n-6))$

b) Analysis of variance for the cubic surface (pure component)

$F(4, n-10) = ((LQC-LQ)/4)/(((T-L)-(LQ-L)-(LQC-LQ))/(n-10))$

Table(5.4.4) Analysis of variance for the significance of trend surfaces : after Krumbein and Graybill (1965), page 336

Table(5.4.5) Generalised equation for the analysis of variance for the significance of trend surfaces ; as described in table(5.4.4).

$$F(k+1,\ n-((k+1).(k+2)/2))) = \frac{ss(k) - ss(k-1)}{ss(tot) - ss(k)} \cdot \frac{n-((k+1).(k+2)/2)}{k+1}$$

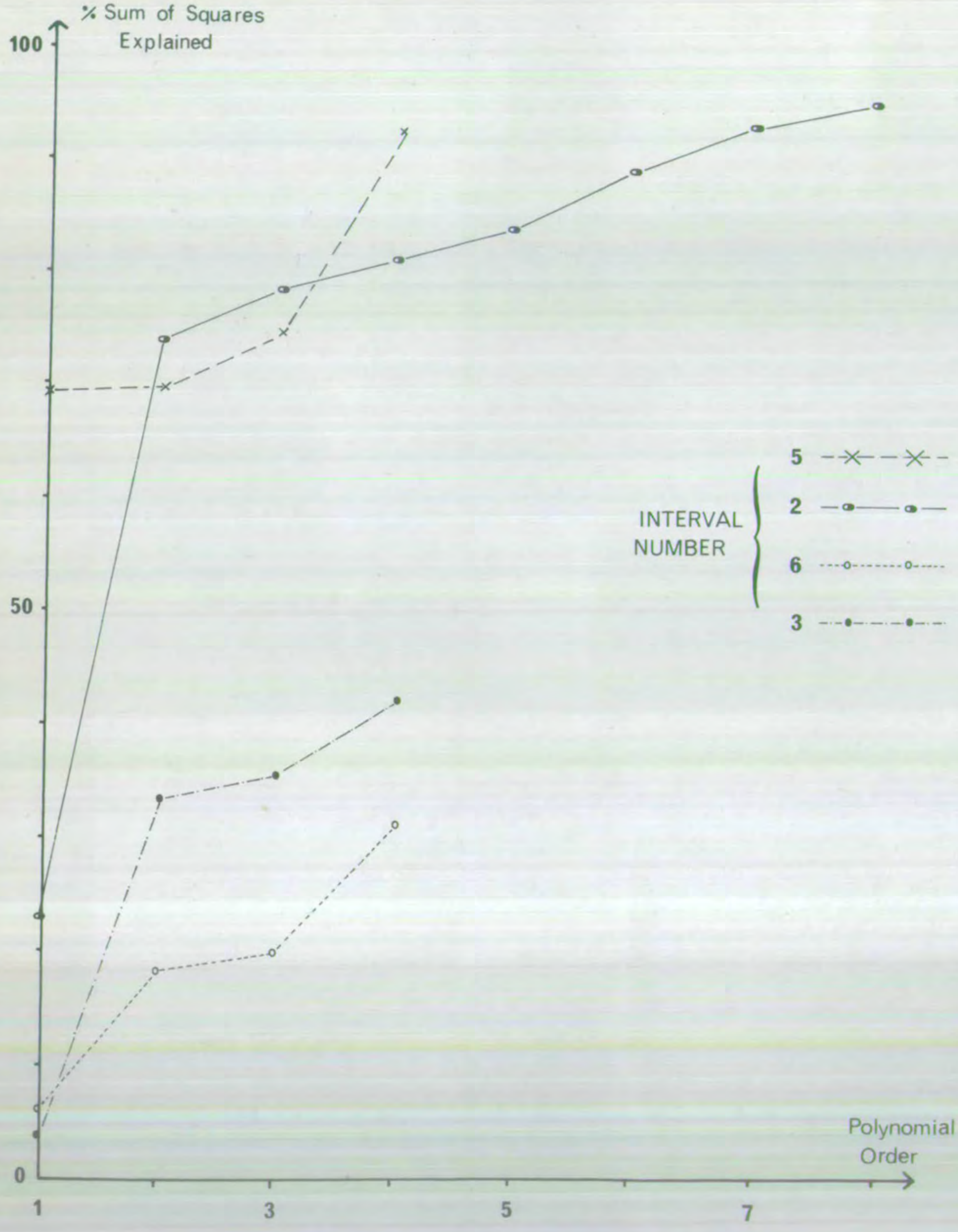
where i) ss(k) = sum of squares associated with the polynomial of full kth. order (ie. containing k,k-1,.....2,1 elements).

ii) ss(tot) = total sum of squares of raw data.

iii) n = total number of points (samples) used to construct the trend surface.

iv) k = order of the polynomial (eg. linear k = 1 ; octic k = 8)

Table(5.4.5)



Figure(5.4.6) Some irregular "fit" curves.

	a	b	c
% Sum of squares explained			
Linear	6.3	69.4	4.0
Quadratic	18.5	69.6	33.6
Cubic	20.2	74.6	36.0
Quartic	31.4	92.5	42.3
'F' ratio			
Linear	4.27@	46.49@	4.58@
Quadratic	6.18@	0.08	32.23@
Cubic	0.64	1.67	1.99
Quartic	3.76@	13.84@	5.68@
Degrees of freedom			
Linear	(2,127)	(2,41)	(2,220)
Quadratic	(3,124)	(3,38)	(3,217)
Cubic	(4,120)	(4,34)	(4,213)
Quartic	(5,115)	(5,29)	(5,208)

Table(5.4.7) Analysis of variance for the significance of three sets of trend surfaces.

@ 'F' ratio significant at 5% level

a Interval 6 ; raw data.

b Interval 5 ; gridded data.

c Interval 3 ; raw data.

In conclusion it would appear that there is no statistical criterion which is not open to criticism of some sort. Fortunately there is an alternative which can be derived simply from a more rigorous definition of objectives.

5.5 An Alternative

It has already been stated (page 38) that areally distributed data should be divided into three components, regional, local and residual. This should be the purpose of trend surface analysis.

Since there are three components, there are three possible approaches to the problem. However, the separation of local from regional plus residual is probably impossible and has been disregarded.

The separation of regional from local plus residual is the aim of most of the criteria for trend selection discussed above. It is probably impossible, however, unless the regional component is by far the strongest or there is some a priori reason for choosing a particular result. McIntyre (1967) stated that the use of maximum likelihood criteria, for the purpose of removing the purely regional component, is illogical because the deviations will, by definition, be correlated where they contain local components.

The separation of regional plus local from residual is more promising. If a trend surface can be produced which has deviations which are residuals, then it must contain an approximation to regional and local components, unless the data are very noisy. Whether or not deviations are residuals can be determined using autocorrelation techniques. For these purposes autocorrelation can be considered to measure the mutual dependence of deviations from the trend surface measured at locations which are geographically closely related. When the autocorrelation coefficient shows that, on average, the change in value from one control point to another is purely random, the deviations can be considered to be residuals. In general terms, it is just as likely at this stage that in moving from any control point to its neighbour the deviation is as likely as not to change sign, so that no large areas of positive or negative deviation remain.

It is important to avoid the misconception illustrated by Miesch and Connor (1967), who stated, "when they (the deviations) are not autocorrelated they are said to represent very local variability, less than the average distance between control points, and to arise from sampling and measurement error" (my insertions). However, since the sampling scheme is predetermined in most cases and the structure of the data not known beforehand, any interpretation should take into account the possibility that the residuals may contain components of considerable magnitude and geological importance.

Although the autocorrelation coefficient is independent of the size of the terms in a series, it may be affected by swamping of one component by another, where the magnitudes are very different. Usually, autocorrelated deviations appear not to be so when the residual component is strongest. Therefore, the effectiveness of the method will vary proportionally to the fit of the surfaces.

Since the data under consideration form a sample rather than target population, serial correlation is substituted for autocorrelation. The serial coefficient could be computed for irregularly distributed data, without Type 1 linearity, if some ordering scheme could be devised. However, since the mean area will not be constant over the whole map, interpretation of the coefficient is virtually impossible. The technique is more readily applicable to gridded data which, as in section (5.2), can be considered to consist of sets of space series. For any set, the serial correlation coefficient can be computed as shown in table (5.5.1), and although only successive members are compared the computational method requires the use of an order of 3; table (5.5.1).

Where the coefficient is more than two standard deviations greater than zero the series is non-random. In this case, the deviations can be considered to be autocorrelated in a particular direction and to contain systematic effects. Trend surfaces of increasing complexity are extracted until all the sets of space series are random. Selected in this way, the final surface contains predominantly regional and local components and its deviations represent residual components, although some mixing arises from the mechanics of the method of least squares.

The method was tested by application to the trend plus deviation data set used previously, considering the 112 control points as two overlapping samples of 56. Figure (5.5.3) shows the simple decrease in coefficients, for series at right-angles, with increasing polynomial order. In all these cases the 'East-West' orientated series became random at cubic, but those directed 'North-South' remained autocorrelated until the sixth order. This sextic surface, for the 20% deviation, supposedly

$$r(k) = n.(\, u(1).u(1+k) + u(2).u(2+k) + \ldots\ldots + u(n-k).u(n))/(n-k).(\, u(1)^2 + u(2)^2 + \ldots + u(n)^2)$$

$$var(\, r(k)\,) = 1/(\, n-k\,)$$

where :-

$r(k)$ = k th. order serial correlation coefficient between members k-1 apart

(adjacent members have $k-1 = 0$)

$var(\, r(k)\,)$ = variance of $r(k)$ in a random series, where n is large.

n = number of terms, $u(i)$, in the series $u(1)\ldots\ldots.u(n)$

Table(5.5.1). Equations for the computation of the serial correlation coefficient and its variance. From Yule and Kendall (1958)

pto

A 3x3 grid is ordered a,b,c,d,e,f,g,h,i in the computer store but on the map it has the configuration :-

c	f	i
b	e	h
a	d	g

The North-South serial correlation coefficient is therefore :-

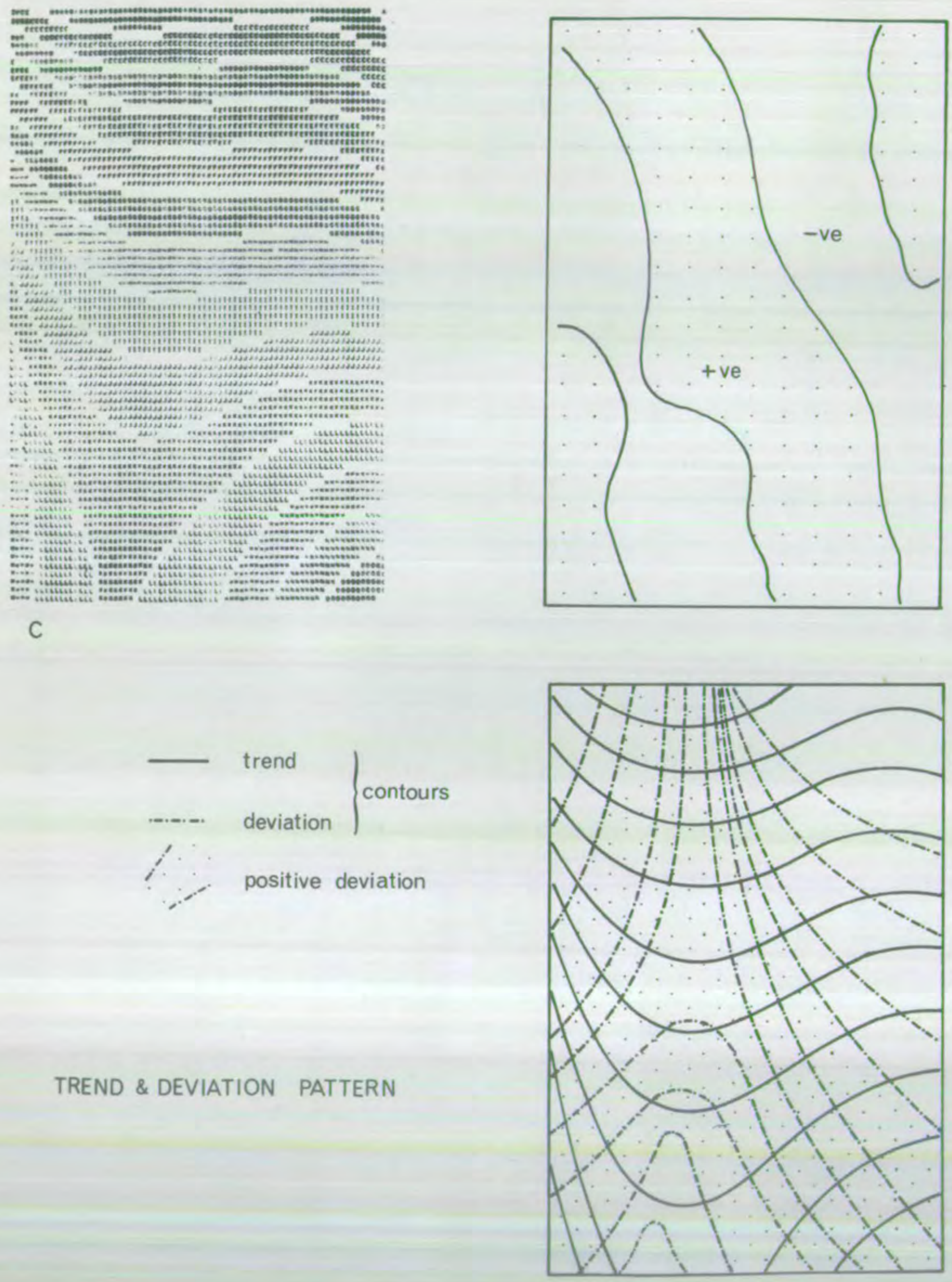
$$r(3) = 9.(a.b+b.c+d.e+e.f+g.h+h.i)/(9-3).(a^2+b^2+c^2+d^2+e^2+f^2+g^2+h^2+i^2)$$

and the East-West coefficient is :-

$$r(3) = 9.(a.d+b.e+c.f+d.g+e.h+f.i)/(9-3).(a^2+b^2+c^2+d^2+e^2+f^2+g^2+h^2+i^2)$$

In both cases a lag of 3 is used rather than 1, which would involve multiplication of unrelated members (e.g. c.d and f.g). This technique is easier to visualise for the East-West coefficient where adjacent map members are separated by two other terms in the linearly ordered series.

Table(5.5.1). Method of mechanical computation of the serial correlation coefficient for gridded data.

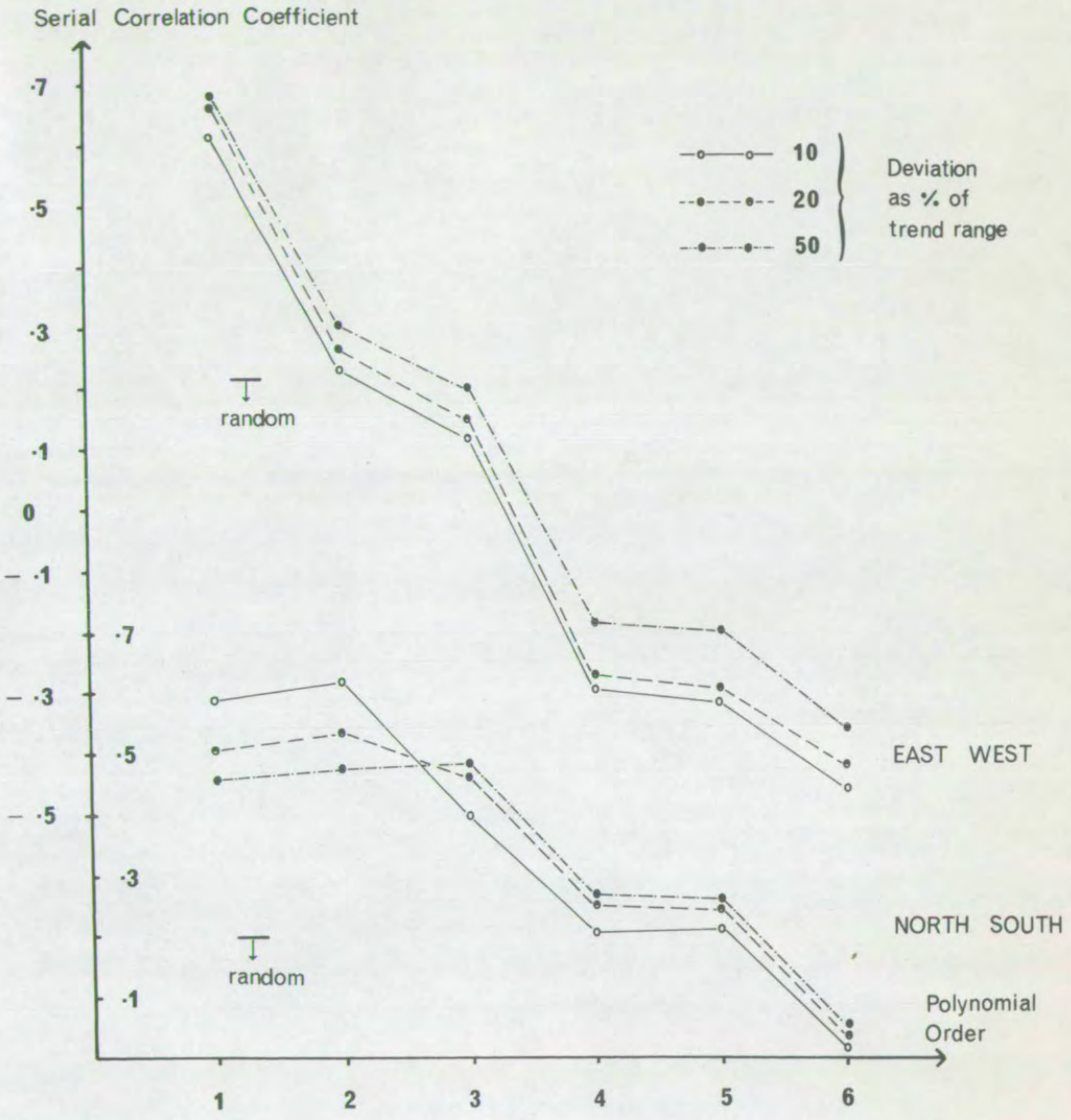


Figure(5.5.2) Cubic component (C) of the sextic trend surface plus its deviations. Original trend plus deviation pattern presented for comparison.

contained regional and local components only, and its computed values were, therefore, resubmitted to trend surface analysis. On an a priori basis the cubic surface was chosen to represent the regional, and its deviations the local components. The results shown in figure (5.5.2) constitute an acceptable approximation to the input, taking into account the complexity of the regional and local components, and they suggest that the method is practicable, at least where the noise level is reasonably low.

In general, since data derived from a maximum likelihood surface contain only regional and local components, the selection of a trend surface, to separate them, should either be based upon some preconceived criterion or the complexity limits described in section (5.1).

An additional advantage in using serial correlation lies in the comparison of the rate of decrease of the coefficient for different sections. Since the coefficient is dependent upon the number of turning points, it can be used to measure the approximate orientation of medium or small scale local components in the deviations, where they have a tendency to be elongate. In figure (5.5.3), the slower rate of decrease in the 'North-South' direction reflects the similar orientation of the deviation pattern used in that experiment. Where computations are made for more sets, inclined at smaller angles, the estimate can become quite realistic.



Figure(5.5.3) Serial correlation coefficients.

5.6 Gridded Samples

If autocorrelation is to be used as the criterion for analysis, then for practical purposes it is necessary to produce a gridded sample from the available information. This may be accomplished by passing a fixed small area (a quadrat) over the map in a regular but discrete fashion, and averaging the data values enclosed at each grid stop. The sample size is, therefore, reduced so that only low order surfaces can be considered non-random for interpretative purposes. However, since just such surfaces are purpose of performing the analysis, and more complex intermediates are computed merely as a means to an end, this objection is not serious.

Gridding is advantageous to autocorrelation techniques because averaging produces data which is much less noisy than its parent. The process tends to push small-scale local components into the residual category, so that contributions from larger-scale (local and regional) components are accentuated in the data submitted for analysis.

The grid sample should form a stable surface independent of the different dispositions of the control points. In other words, gridding is unjustifiable where the distribution is anisotropic, especially where this arises from Type 1 linearity. It is impossible to put any limit on the amount of permissible anisotropy, since in every case it will partly depend upon the number of observations.

Vistelius (1966 p.67) considered that stability criteria are threefold, and depend upon:-

a) The interval between observations,

b) Number of points falling into each quadrat,

c) Weighting scheme employed.

The first two factors are not independent and may be considered together as the problem of selecting the correct size of quadrat. Clearly, if the size is too small the averages will contain as much variability as the raw data does, if too large interesting variability will be lost. The interesting variability, apart from the regional component, will consist at worst of a whole range of local components of different scale and magnitude. Since it will be practically impossible to separate these, the interesting variability can be considered as the local components with the largest magnitude.

Krige (1966 p.15), an exponent of the method of moving averages, admitted that "..... common sense dictates that if ..... samples ..... could be increased in size ..... the extreme variation ..... would decrease and at some stage an optimum size ..... sample would be obtained .....". Whatever size of quadrat is employed, Krige's (1966 p.17) additional claim, that averaging, in itself, can produce non-autocorrelated deviations, must be dismissed as a gross oversimplification.

Methodology, regarding quadrat sizes, has been developed in the Biological and Ecological sciences, but is not applicable to map analysis since it is based on frequency, rather than frequency and value. For example, if data are distributed randomly a quadrat of twice the mean area (Curtis and MacKintosh 1950) will convey the most information but not necessarily provide the best sampling scheme. However, this seems to be a logical starting point from which to increase the quadrat size until the optimum is reached.

If the averages are to be most meaningful, the variance within the quadrats should be minimised. This can be achieved only where the size approximates the scale of the large-magnitude local components (the interesting variability). As the quadrat size approaches and passes this value, the within-quadrat variance should fall and rise. The analysis of variance is suggested and the technique employed is an extension of the nested sampling schemes of Potter and Siever (1955) and Krumbein and Tukey (1956).

The F ratio, in the analysis of variance, can be considered to consist of two components, as illustrated in figure (5.6.1). For a fixed number of control points, the F ratio will decrease with an increase in the number and, therefore, a decrease in the size of the quadrats, although the ratio of sums of squares remains constant. As the sum of squares <u>within</u>-quadrats falls and rises, the ratio of sums of squares of <u>between</u>-quadrats over <u>within</u> reacts antithetically, causing the smooth curve (of the ratio of degrees of freedom against quadrat size) to become irregular, with the largest departure where the optimum is attained. During computation the quadrat shape is made the same as that of the map, and the sampled area allowed to deviate slightly from the map area since redundant quadrats can easily be discarded from the analysis.

The technique was checked using two sets of artificial data. In the first 72 randomly distributed points were given values so that the data contained a large-magnitude local component, on the scale of about

For the analysis of variance :-

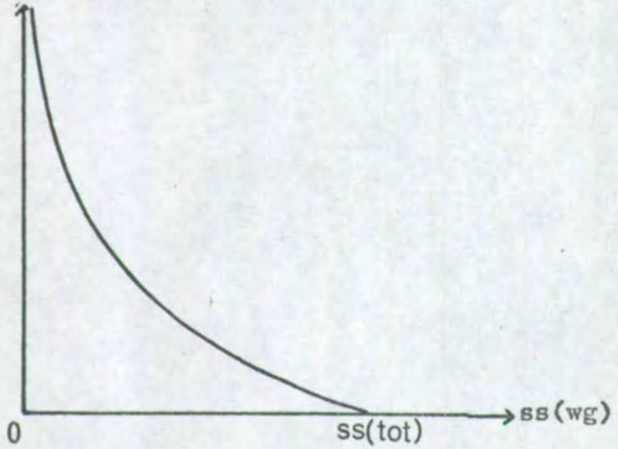
$$F\alpha(k-1,n-k) = (ss(bg)/(k-1))/(ss(wg)/(n-k))$$

This equation can be re-arranged to give :-

$$F\alpha(k-1,n-k) = ((ss(tot)-ss(wg)).(n-k))/(ss(wg).(k-1))$$

This equation consists of two components :-

(a) the ratio of sums of squares
((ss(tot)-ss(wg)))/ ss(wg)

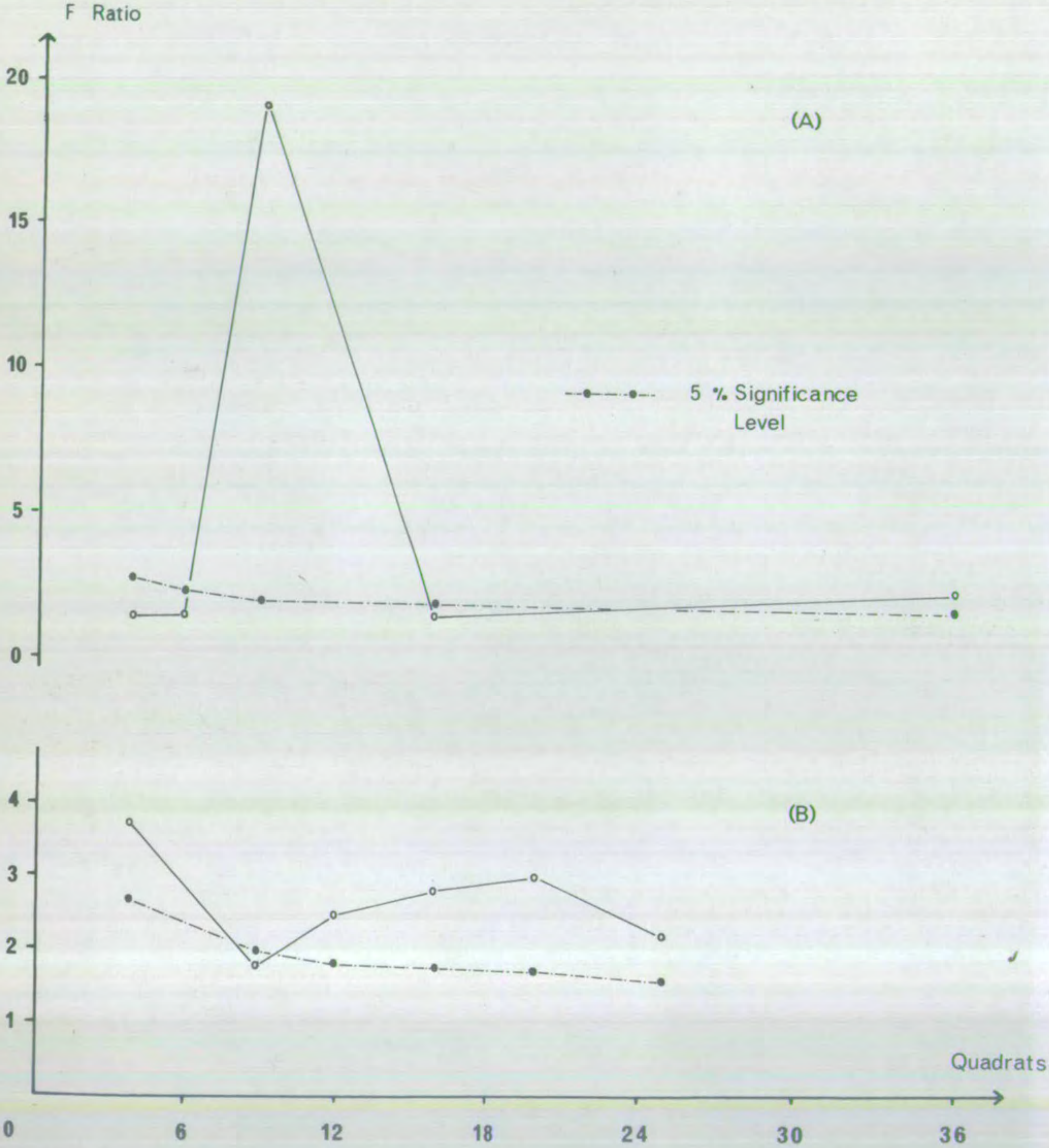


(b) the ratio of degrees of freedom
(n-k)/(k-1)

Figure(5.6.1). The components of the F ratio of the analysis of variance

ss = sum of squares : tot = total : wg = within groups

bg = between groups : n = sample size : k = number of groups

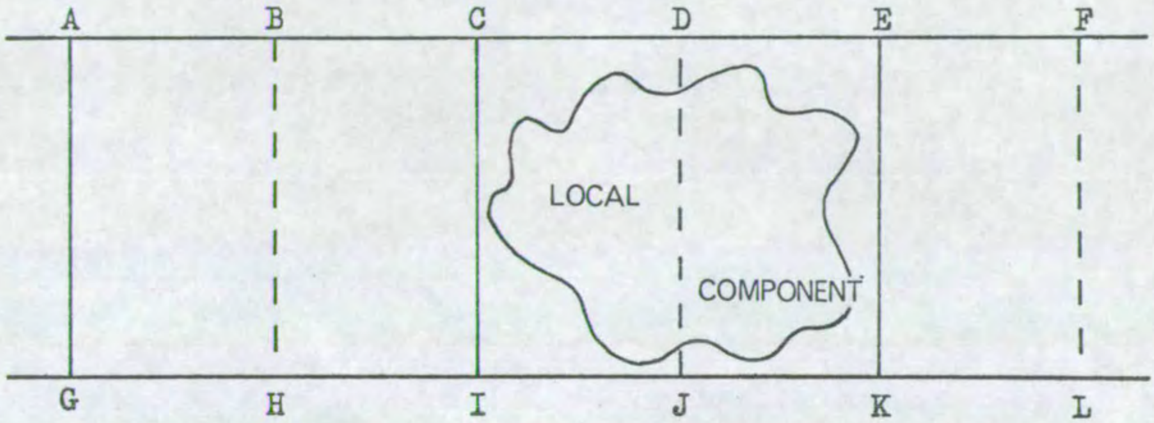


Figure(5.6.2) F ratios for quadrat sizes.

1/9th of the map area, positioned so that the correct quadrats would enclose it exactly. The result is shown in figure (5.6.2). In the second, 100 points, with a local component of 1/20th of the map area offset relative to the grid system, were produced from random number tables. The result is shown in figure (5.6.2). In both cases the correct prediction was made.

The final critical factor mentioned by Vistelius (1966 p.67) was the nature of the weighting scheme. He considered as "obvious" a scheme where the weights attached to data vary inversely with increasing distance from the quadrat centre. This is not strictly true where the data are noisy. For example, residual exaggerations, occurring by chance near the centre, will be considered more important than more realistic values throughout the rest of the quadrat, and will be weighted accordingly. In this way the arithmetic average could be distorted, possibly out of all reality. It is perhaps more realistic not to attach any greater significance to any particular point but to consider the gridded data sets as members of a dimensionless array (Preston 1966).

During applications of the gridding technique the selected quadrat was advanced by only half its own width, in order to solve the problem of offset between the arbitrary grid system and the position of the local components; see figure (5.6.3). In this way larger sample sizes were obtained. Grouping within quadrats was accomplished using the geometric mean, since this gives a better estimate of the true mean than its arithmetic counterpart where occasional extreme values are encountered.



a) Overlapping scheme

i)	Nearest miss	ACGI
ii)	Worst intermediate	BDHJ
iii)	Best overlap	CEIK

b) Non-overlapping scheme

i)	Best result	ACGI , CEIK , etc.
ii)	Worst result	BDHJ , DFJL , etc.

Figure(5.6.3) Comparison of overlapping and non-overlapping sampling schemes, when quadrat size is the same as large magnitude local components.

5.7 Conclusions

The scale factor, often disregarded in an analysis of mapped data, can be used to redefine the terms regional, local and residual, in such a way that they will always be valid within the frames of reference of any study. Some tentative complexity limits can be suggested for regional components, based on the axiom that they cannot be repetitive. Similar limits for non-random trend surfaces can be constructed using the constraint of the number of observations.

Most trend selection criteria can be shown to be impractical or statistically unjustifiable for anything other than the computation of predictive surfaces. However, the "percent sum of squares explained" parameter can be used as a guide to the noise level of the information available.

Simulation tests have been used to show that areally distributed data can be successfully trisected if the residual component is removed before regional and local components are separated on some predetermined basis. Randomness amongst deviations, which must be proved before the residual component can be extracted, is probably more complex than can be described by simple size frequency measurements. Where the noise level is not excessive, autocorrelation can be used to estimate the extent to which deviations, located along the principal directions of gridded samples, exhibit randomness. This technique avoids the illogicality of employing maximum likelihood criteria to separate regional from local plus residual components.

Further simulation tests have shown that the clustering of observation localities about a line can produce physical distortions in an apparent trend surface. Other forms of clustering do not have this effect. However elongate the control strip, the trend surfaces remain statistically unbiased where the collection locality co-ordinates refer to the margins of the smallest rectangular control area. In this case the correlation coefficient measured between the observation locality co-ordinates remains insignificant. With respect to the margins of a map containing the control strip, the trend surface is not statistically acceptable because the co-ordinate correlation is numerically large. Geological interpretations based on this type of data can be totally misleading.

The addition of a few extra, well distributed observations to a map containing a control strip can lead to realistic results even though the co-ordinate correlation remains high. For use as a guide to the data linearity, and thus the potential distortion, the correlation between observation co-ordinates must be treated with care. It is important to draw the distinction between the two types of linearity ("Types 1 and 2"), and failure to do this can lead to the rejection of apparent trend surfaces which are reasonable simulations of their real counterparts.

Distortions arising from linearity are greatest where the data are very noisy. In fact, it appears that the noise level in the raw data is probably the greatest difficulty in the application of successful trend surface analysis. If the regional component is very weak, compared to the smaller scale components, then it is not surprising that the

the analysis sometimes produces spurious results, under conditions which are analogous to those encountered when trying to extract a trend from randomly generated data.

It is concluded that trend surface analysis can be a useful technique, provided that the objectives of the analysis are rigorously defined and the data are sufficient to reach statistically and geologically justifiable conclusions regarding those objectives.

STATISTICAL COMPARISON OF INTERVALS

6.1 Introduction

The comparison of isopach maps in section (4) suggested that in some cases at least the thicknesses of adjacent intervals are related. If the truth of this assertion can be demonstrated quantitatively then important assumptions, regarding the controls over sediment accumulation, can be made.

Simple regression could not be used to measure correspondence because the samples, from which the isopachs were constructed, did not have identical sizes or distributions and the data would have to be screened before processing. Screening involves a loss of reproducibility and should be avoided wherever possible. Furthermore, correspondence arising on one scale may be swamped by random fluctuations arising on different scales. In addition, the separation of the different scale components provides a valuable insight into what may be the underlying processes.

Therefore, it appears that it is necessary to produce standardised samples and to separate the scale components of variance, before statistical comparisons of neighbours can be made in such a way as to supply the most information. Using the principles outlined in section (5) both requirements can be met using trend surface analysis.

6.2 Raw Data

In accordance with the conclusions reached in section (5) the subsets of raw data from each interval were tested for bias. Of the correlation coefficients, between the co-ordinates of the observation localities, listed in table (6.2.1), two are significant at the 5% level, one at 1% but none at the 0.1% level. The distribution of the observation localities in each of the subsets is similar to the distribution of the total data set, figure (2.0.1), and the correlations, therefore, refer to Type 2 linearity. Comparison with figure (5.3.10) suggests that the distortions arising from this degree of Type 2 linearity can probably be ignored.

Figure (6.2.2) shows the reduced major axes of the seven distributions and, therefore, the potential direction of distortion. All except one are virtually collinear, so that if any distortions did arise they would be with the same sense and, therefore, be cancelled out when comparisons are made. The oblique axis, for interval 5, refers to the distribution with the smallest correlation coefficient, and thus for practical purposes the error introduced should be negligible.

The total or sampled population, figure (2.0.1), reflects Type 2 rather than Type 1 linearity, since the map and control areas are almost identical. Clustering in the West and South-East, with a notable area of weak control in the East, is not as extreme as in the 'clusters' distribution of the second simulation test (section 5.3). The distortion produced by clustering should not, therefore, be significant even though

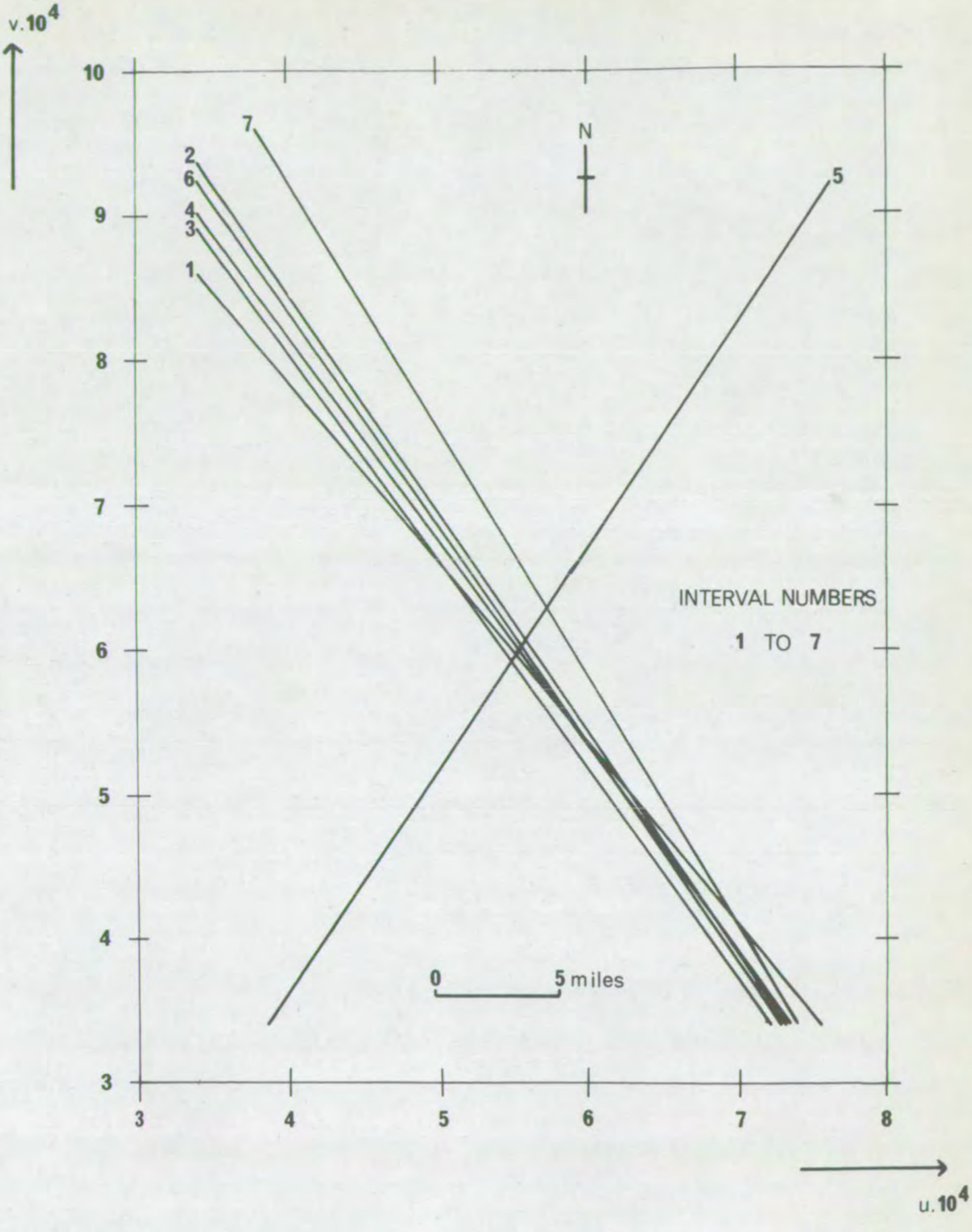
Interval	Interval number	Sample size	Correlation	Normality
Ch to CCMB	7	114	-0.221@	16.23
RS to Ch	6	130	-0.064	10.28$
DS to RS	5	178	0.008	67.28
DH to DS	4	206	-0.059	46.36
Pk to DH	3	239	-0.153@	32.86
T to Pk	2	243	-0.080	12.89$
Tq to T	1	191	-0.192@@	40.96

Table(6.2.1) Raw data statistics ; East Midlands Coalfield.

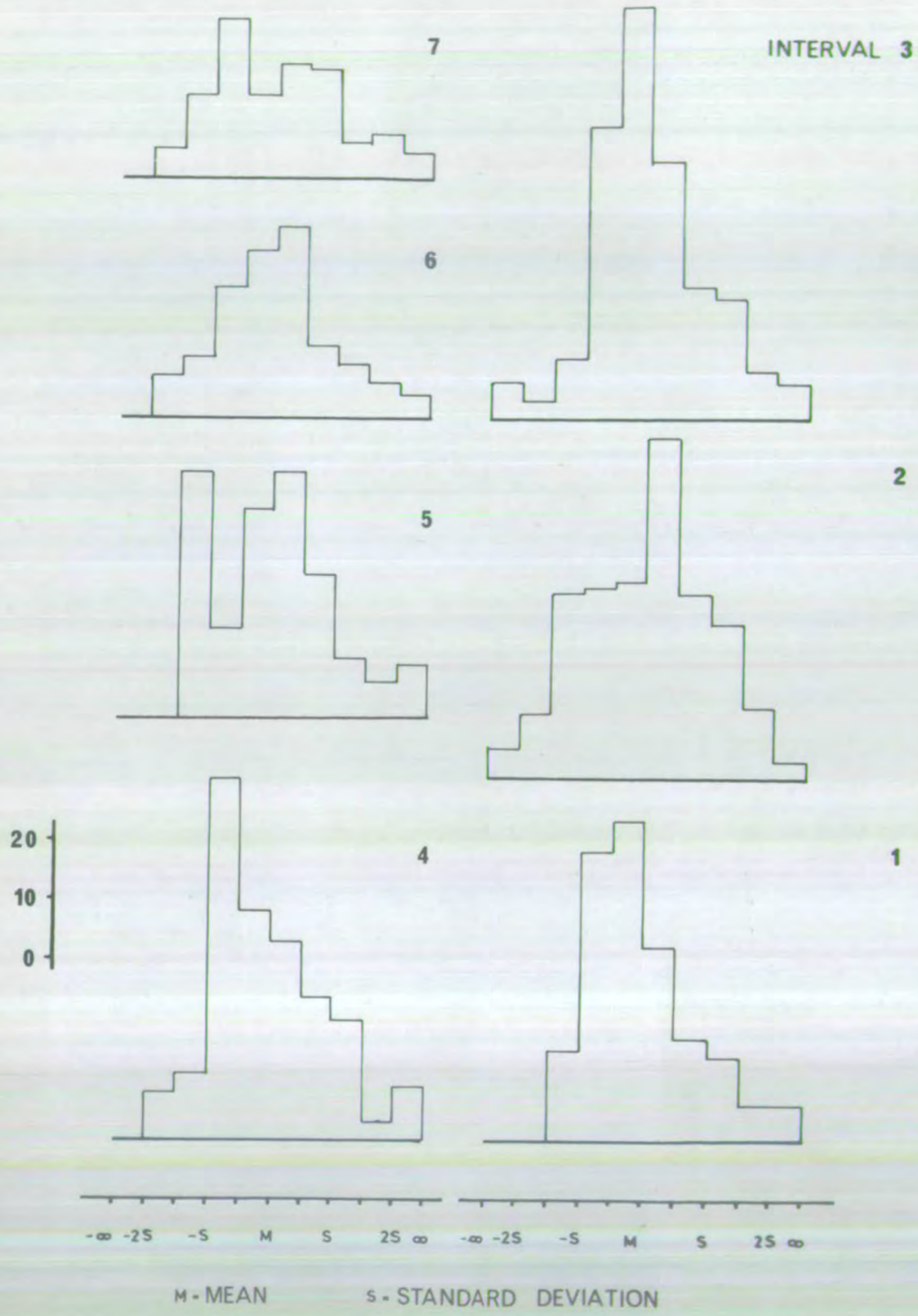
@ co-ordinate correlation significant at 5% level

@@ co-ordinate correlation significant at 1% level

$ chi square (7 degrees of freedom) insignificant at the 5% level ; raw data, therefore, is normally distributed.



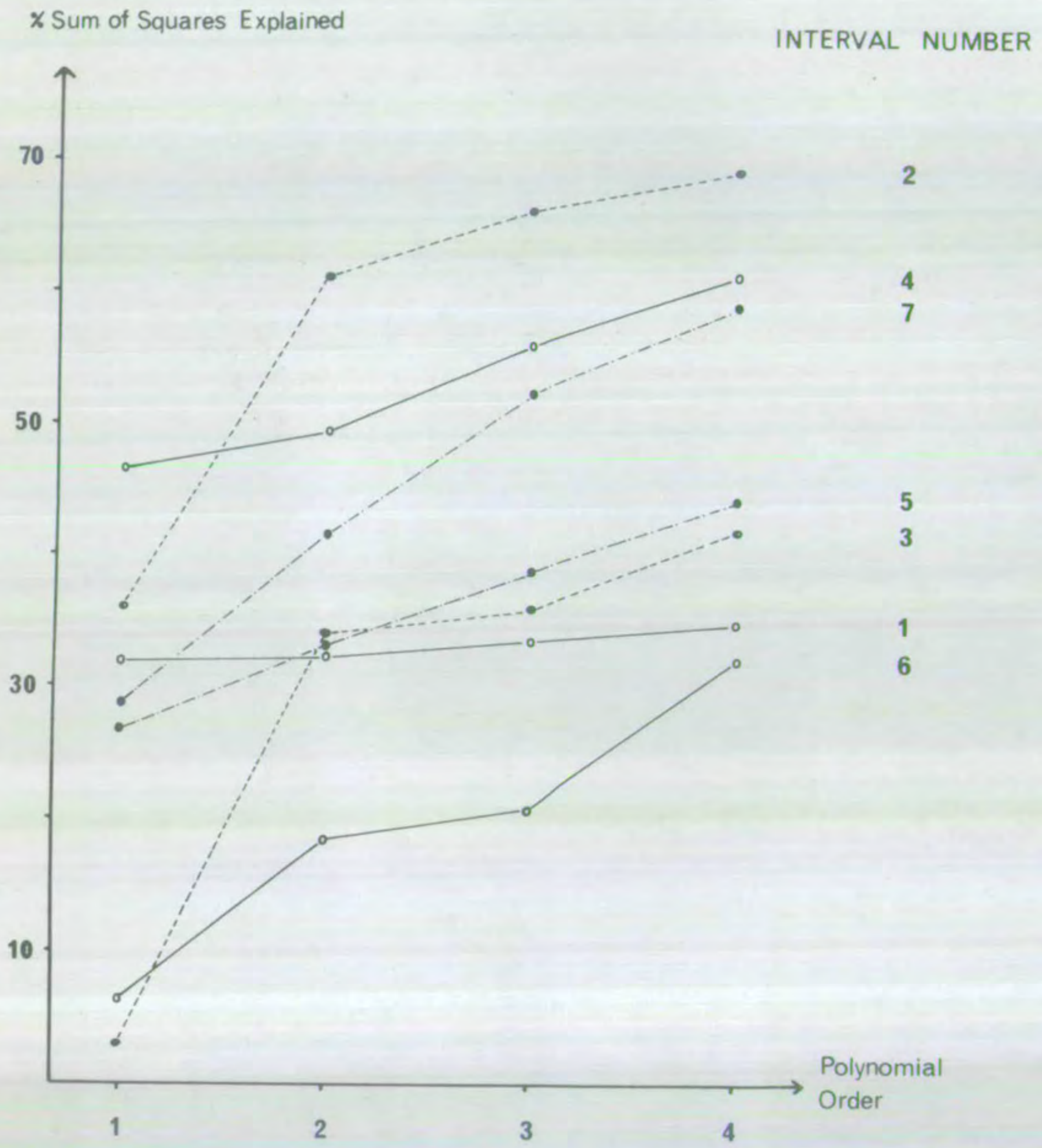
Figure(6.2.2) Reduced major axes of data point distributions of the 7 intervals.



Figure(6.2.3) Size frequency distributions of the raw data from the 7 intervals.

the data is much noisier than in the artificial simulation test. However, areas of zero control, in the South-West and North-West particularly, allow the possibility of the surfaces going "wild", especially when high order polynomials are computed.

A check was made on the normality of the observed data presented for analysis, since the significance of the correlation coefficients, computed as a means of comparison, can only be assessed where the populations concerned are normally distributed. The results, listed in table (6.2.1), show that five of the subsets are not normal at the 5% level. The largest departures occur where the intervals contain thick belts of sandstone which give rise to positive skewness in the associated size-frequency distributions. However, the thick sandstones of interval 2 are so widespread that their effect is regional and the resulting distribution normal. The upper, more muddy intervals (numbers 6 and 7) are less skewed but polymodality causes departures from normality. Since the basic data is, in general, not normally distributed, the significance of comparisons based on correlation coefficients must be treated with care. However, the histograms shown in figure (6.2.3) do not depart grossly from normality and, therefore, the computed significance levels may not be totally unrealistic. The distributions are clearly not all lognormal so that the transformation suggested by Bokman (1957) cannot be applied.



Figure(6.3.1) "Fit" of trend surfaces extracted from the raw data.

6.3 Trend Surface Analysis of Raw Data

Trend surfaces up to quartic order were extracted from the raw data in order to estimate the noise levels and to provide some reference for the interpretation of the results of more sophisticated analysis.

The amounts of explained variance of these surfaces, figure (6.3.1), are small, the maximum quartic fit being below 70%. The level of noise in the information must, therefore, be high and it is unlikely that any analysis could be successfully completed on the data in this form. This is not a surprising result since, like most other geological data, a whole gamut of processes are probably involved, operating on different scales and magnitudes.

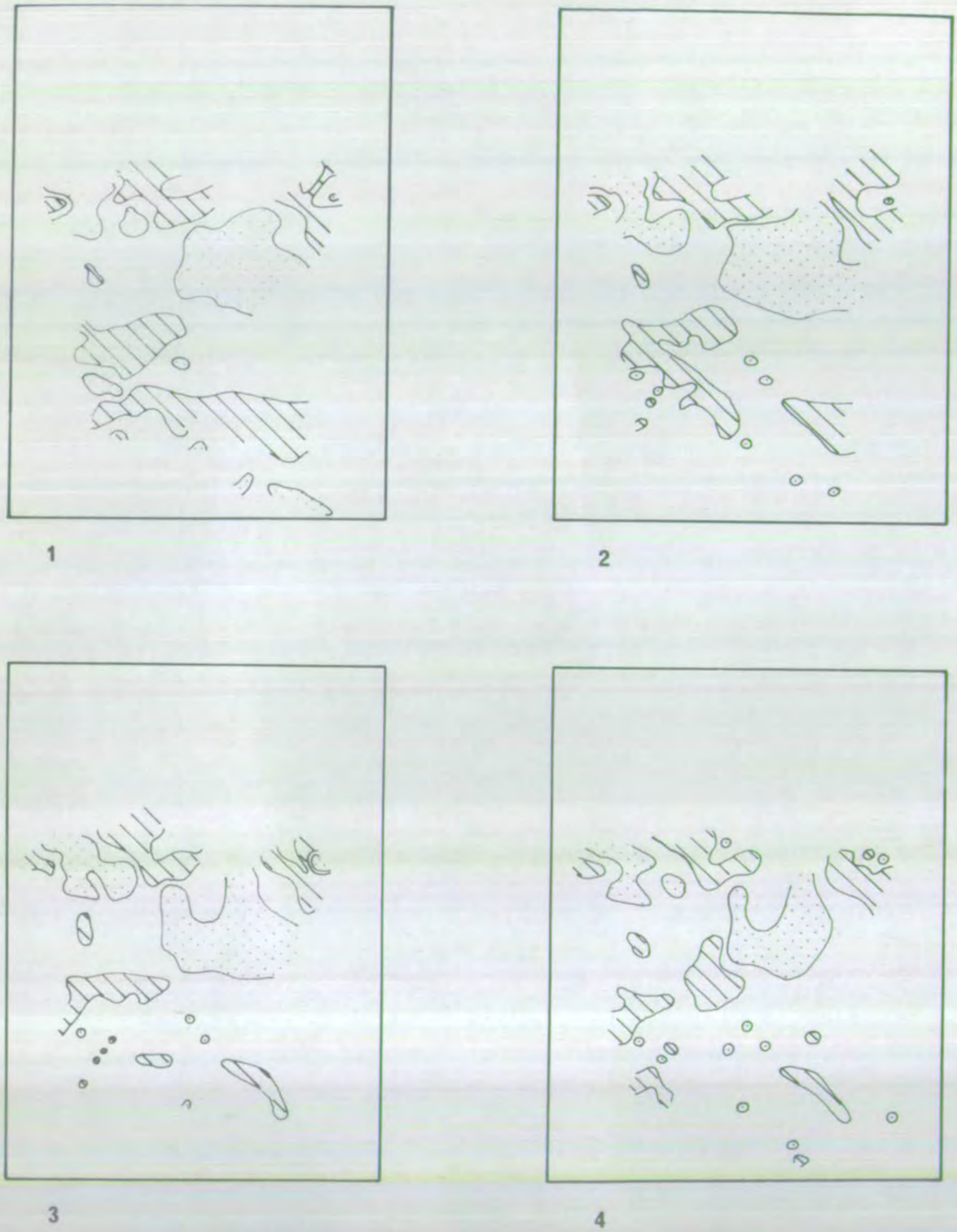
The trend surfaces, shown in figures (6.3.2(a)) to (6.3.8(a)), can be used to illustrate and explain the variations in amounts of explained variance. The computer output can be interpreted in terms of the information in table (6.3.9). The fit curves for intervals 2 and 3, figure (6.3.1), show a marked increase between linear and quadratic which reflects the symmetry of the regional processes within the map area. On the other hand, the almost flat curve for interval 1 suggests that the map area illustrates only part of a process operating over a much larger area. Similar results for intervals 4 and 5 show that thick sandstones must in some cases be taken up within the trends even though they are restricted to belts. The take-up of local processes by the trends can cause extreme distortion, as in the case of interval 5 where the linear trend increases towards the South-West.

Maps of deviations from trend surfaces were produced on a CALCOMP 564 drum plotter working off-line to a KDF 9 computer, the trend analysis and plotting programmes being linked via magnetic tape. For rapid production and plotting accuracy, symbols were used to show how far any particular reading deviated from the mean, in units of one standard deviation. The areas of positive, negative and zero deviation from the trends were then simply grouped by hand, figures (6.3.2(b)) to (6.3.8(b)).

While the areas of similar deviation progressively decrease in size with increasing polynomial order, some maps are remarkably stable with persistent 'highs' and 'lows', while others vary appreciably. In some cases, features which disappear with a step up in polynomial order may reappear at even higher orders. Clearly, therefore, the result of any comparison will depend critically upon the surfaces selected to separate the components of variance.

One general observation of interest is that, with the probable exception of interval 2, the larger areas of deviations, for all surfaces, tend to be located where the linear surface indicates maximum thickness. In many cases this lies towards the centre of the Pennine Basin as defined by Wills (1956).

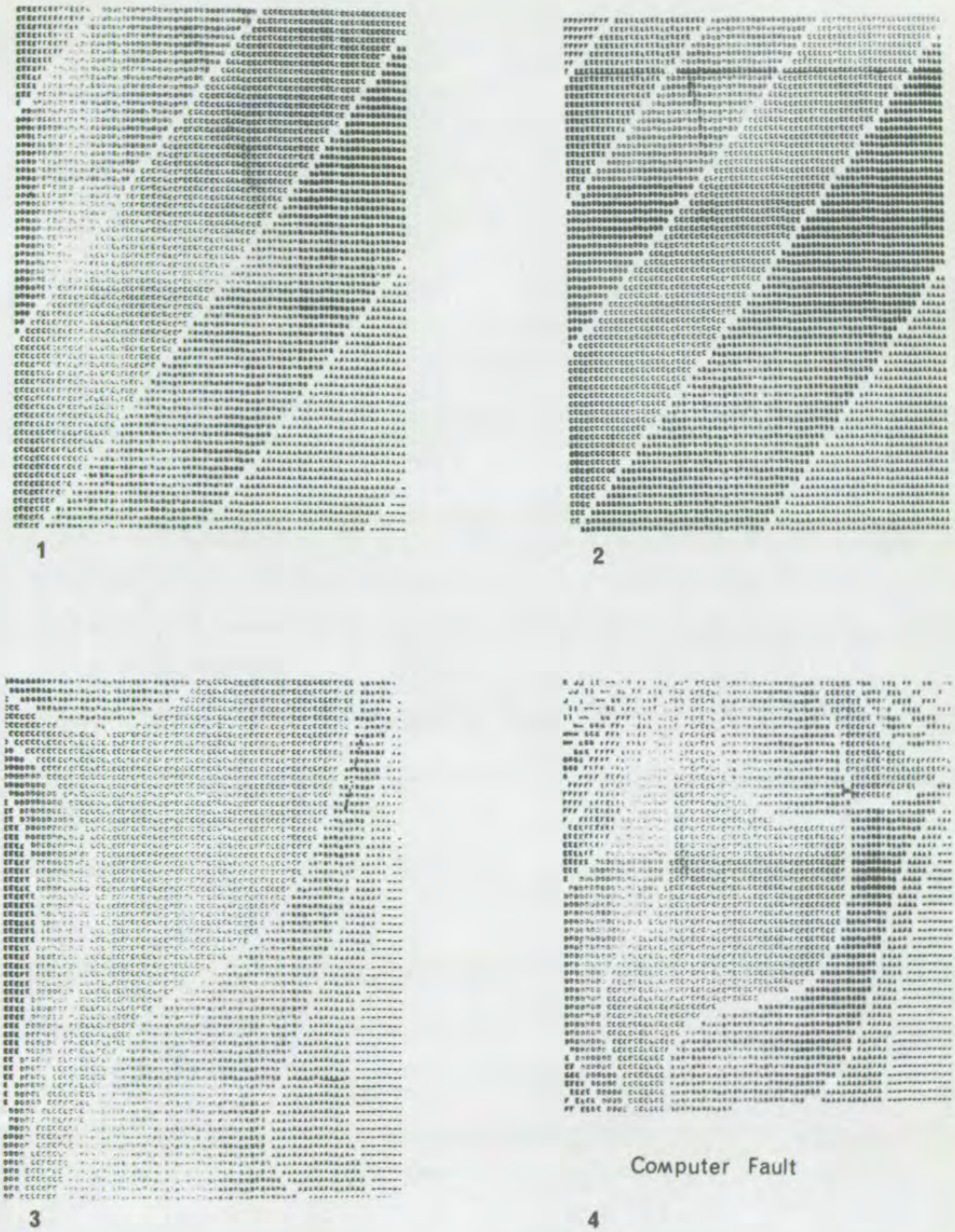
Sandstones appear as areas of positive deviation only when they are very thick (greater than about 50 feet) and where they are so restricted that they cannot be completely explained by the trend.



Figure(6.3.2b) Deviations from trend surfaces extracted from raw data (orders 1 to 4). Interval 1, Three-quarters to Tupton coal.

stippled deviation more than ½ standard error above mean of deviations.

hatched deviation more than ½ standard error below mean of deviations.



Figure(6.3.2a) Trend surfaces of order 1 to 4 ; raw data, total thickness of interval 1.

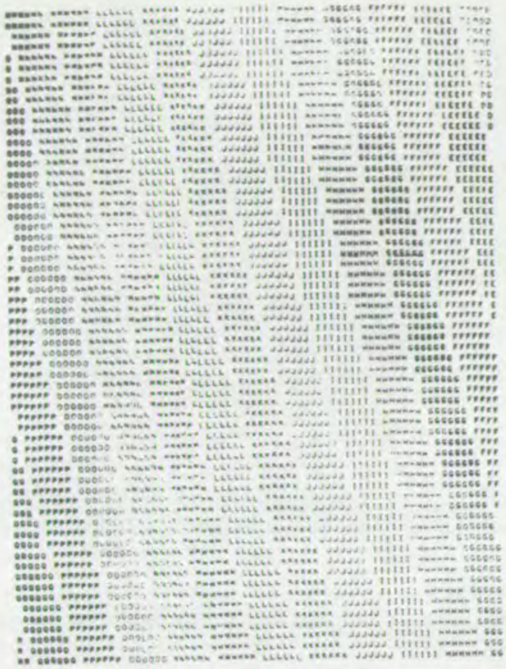
1

2

3

4

Figure(6.3.3b) Deviations from trend surfaces extracted from raw data (orders 1 to 4). Interval 2, Tupton to Parkgate coal.
For key see figure(6.3.2b).



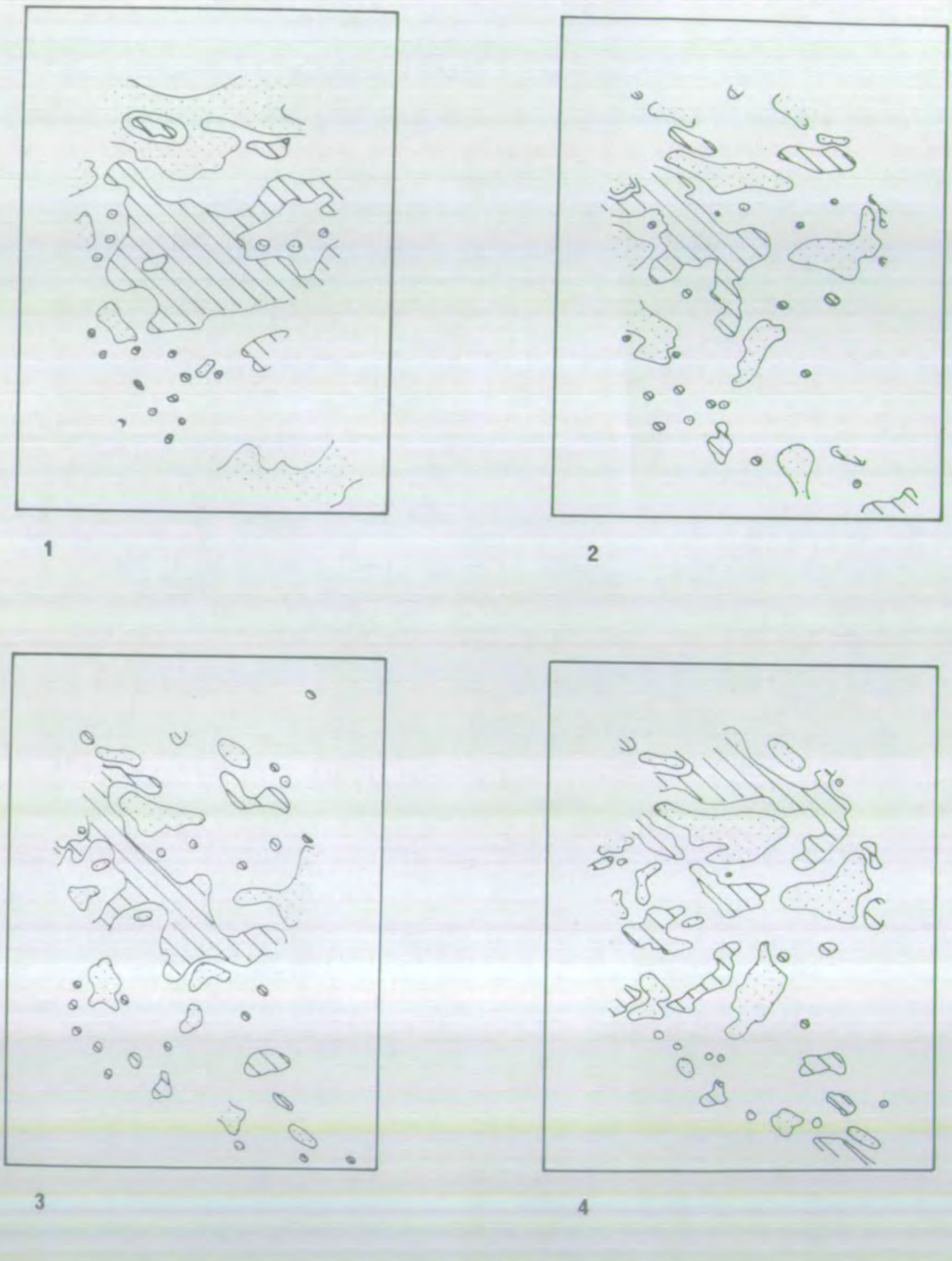
1

2

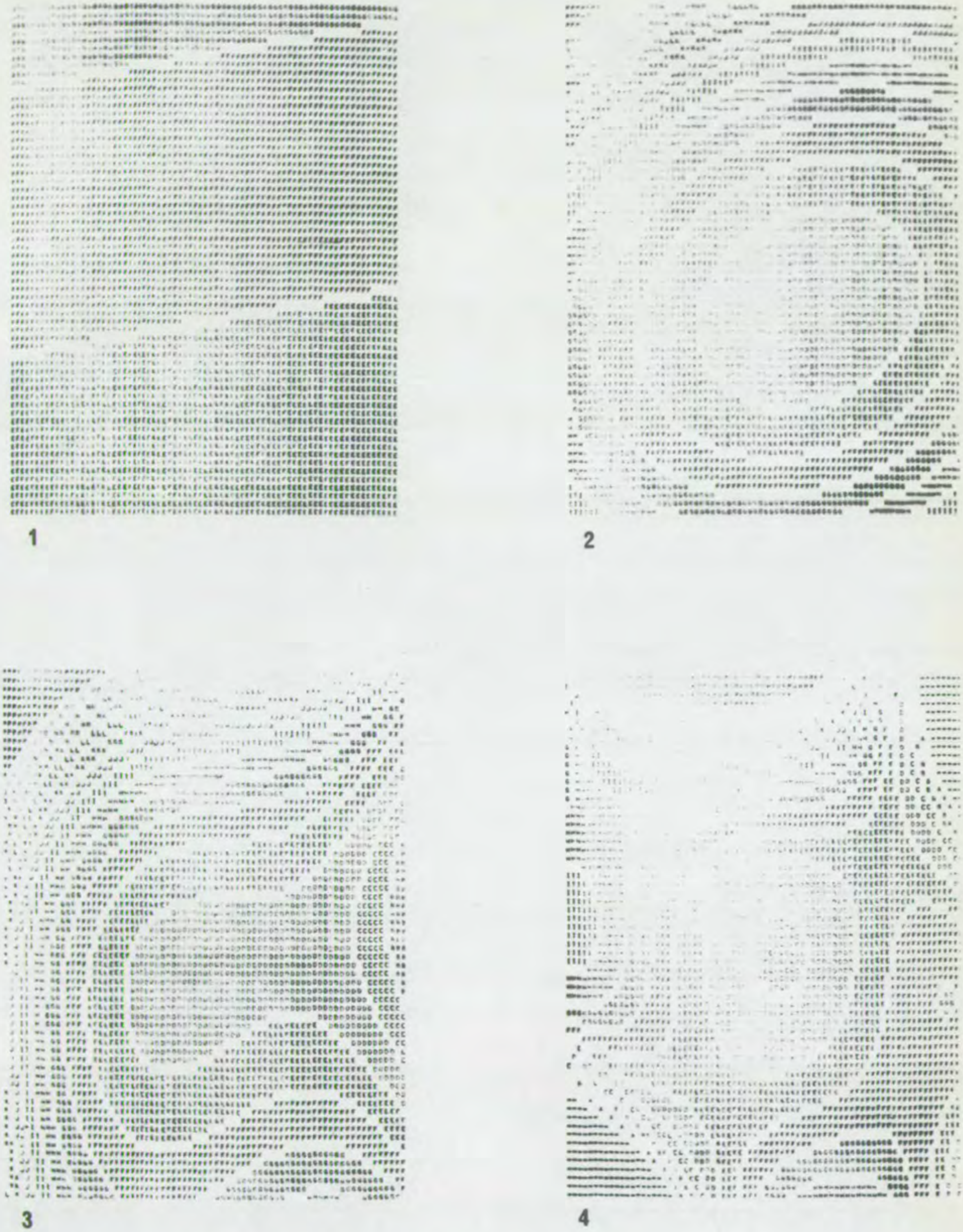
3

4

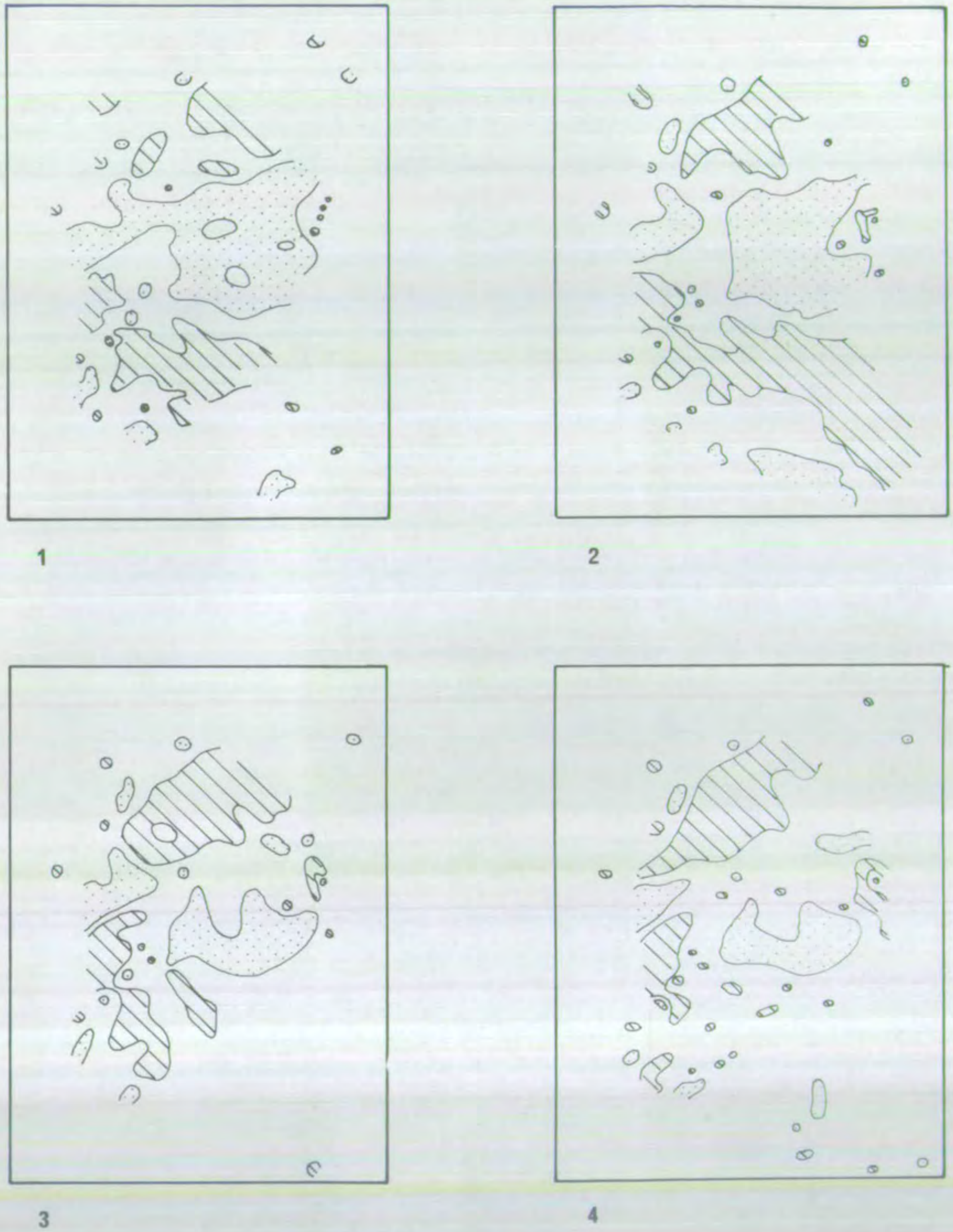
Figure(6.3.3a) Trend surfaces of order 1 to 4 ; raw data, total thickness of interval 2.



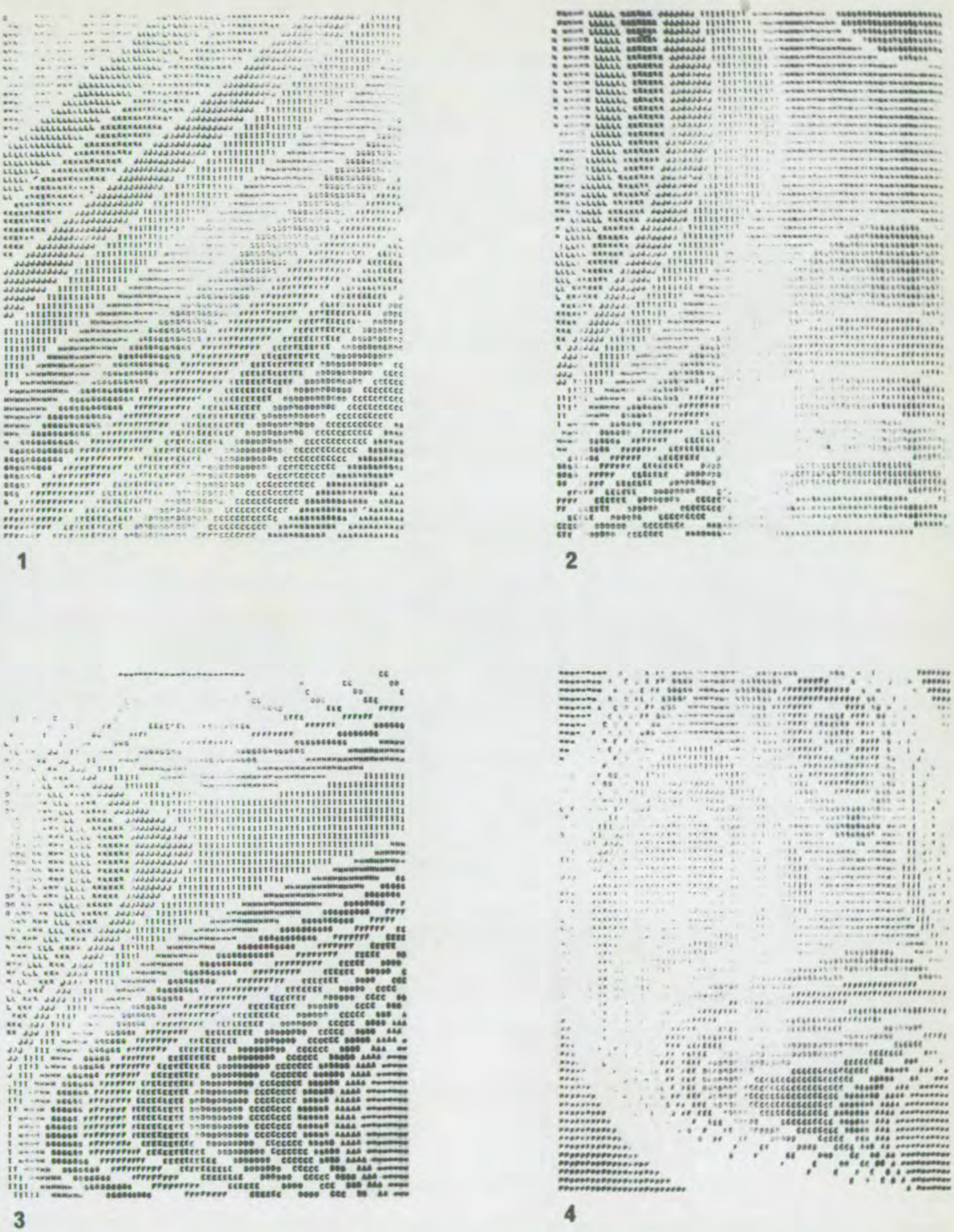
Figure(6.3.4b) Deviations from trend surfaces extracted from raw data (orders 1 to 4). Interval 3, Parkgate to Deep Hard coal.
For key see figure(6.3.2b).



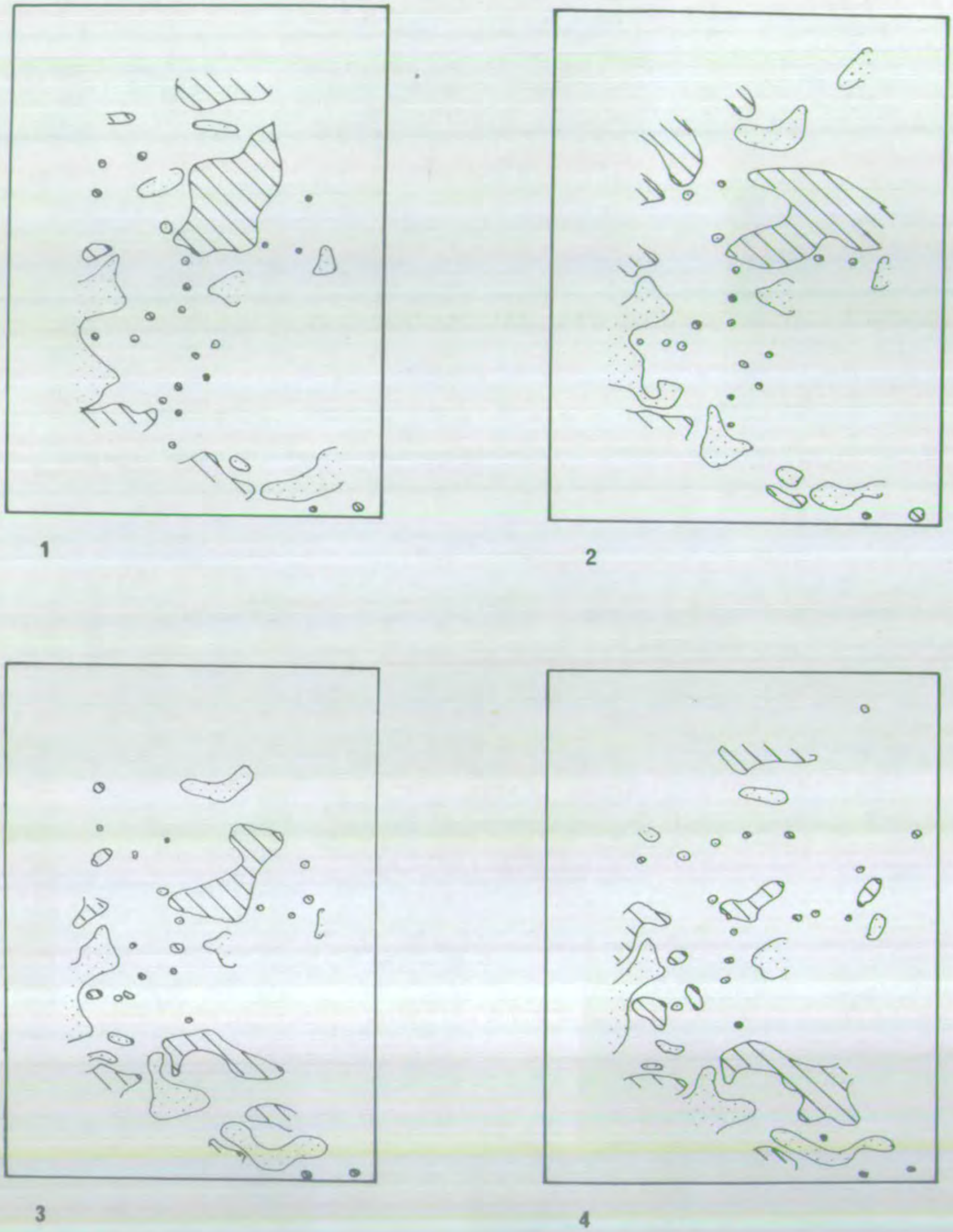
Figure(6.3.4a) Trend surfaces of order 1 to 4 ; raw data, total thickness of interval 3.



Figure(6.3.5b) Deviations from trend surfaces extracted from raw data (orders 1 to 4). Interval 4, Deep Hard to Deep Soft coal.
For key see figure(6.3.2b).

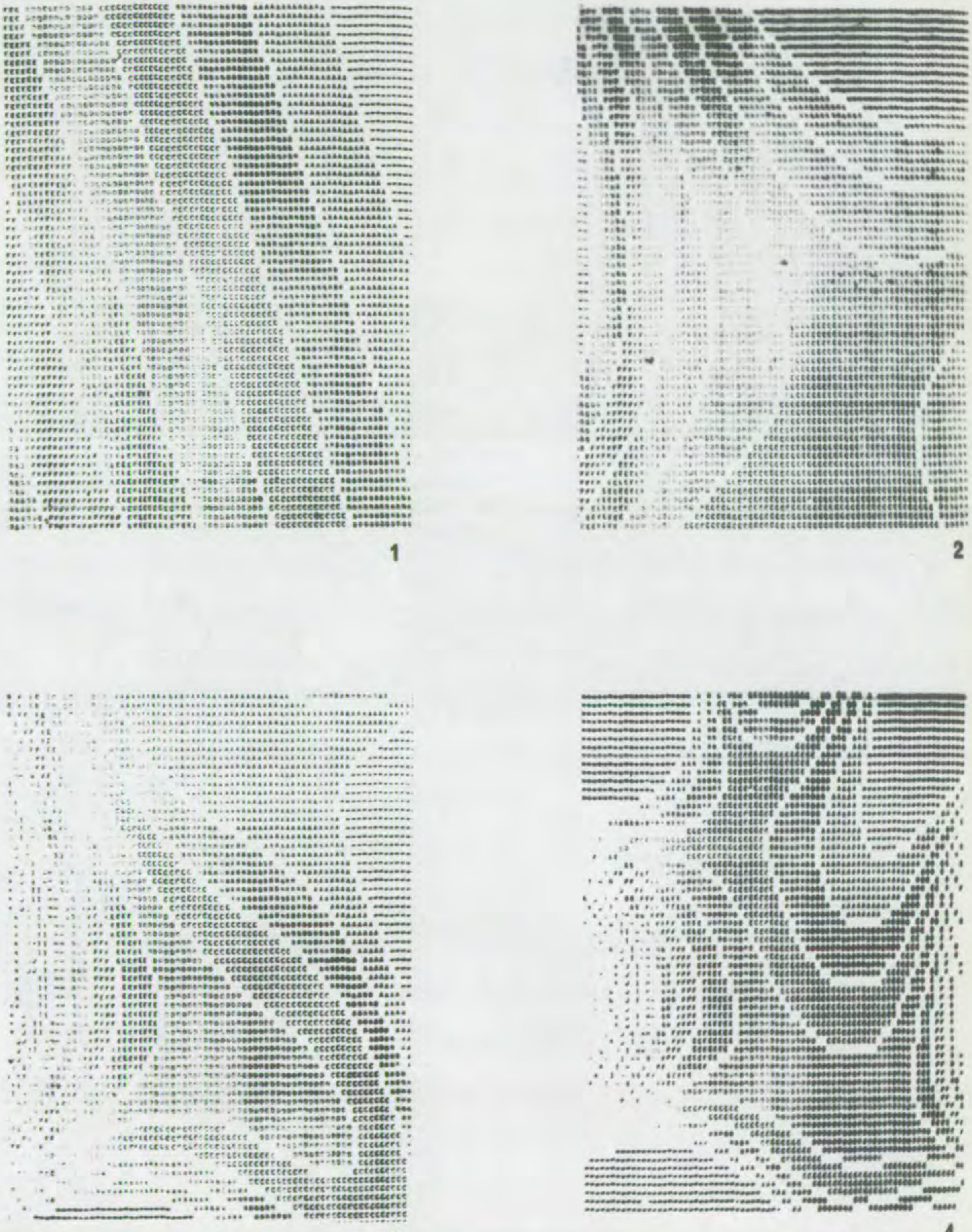


Figure(6.3.5a) Trend surfaces of order 1 to 4 ; raw data, total thickness of interval 4.

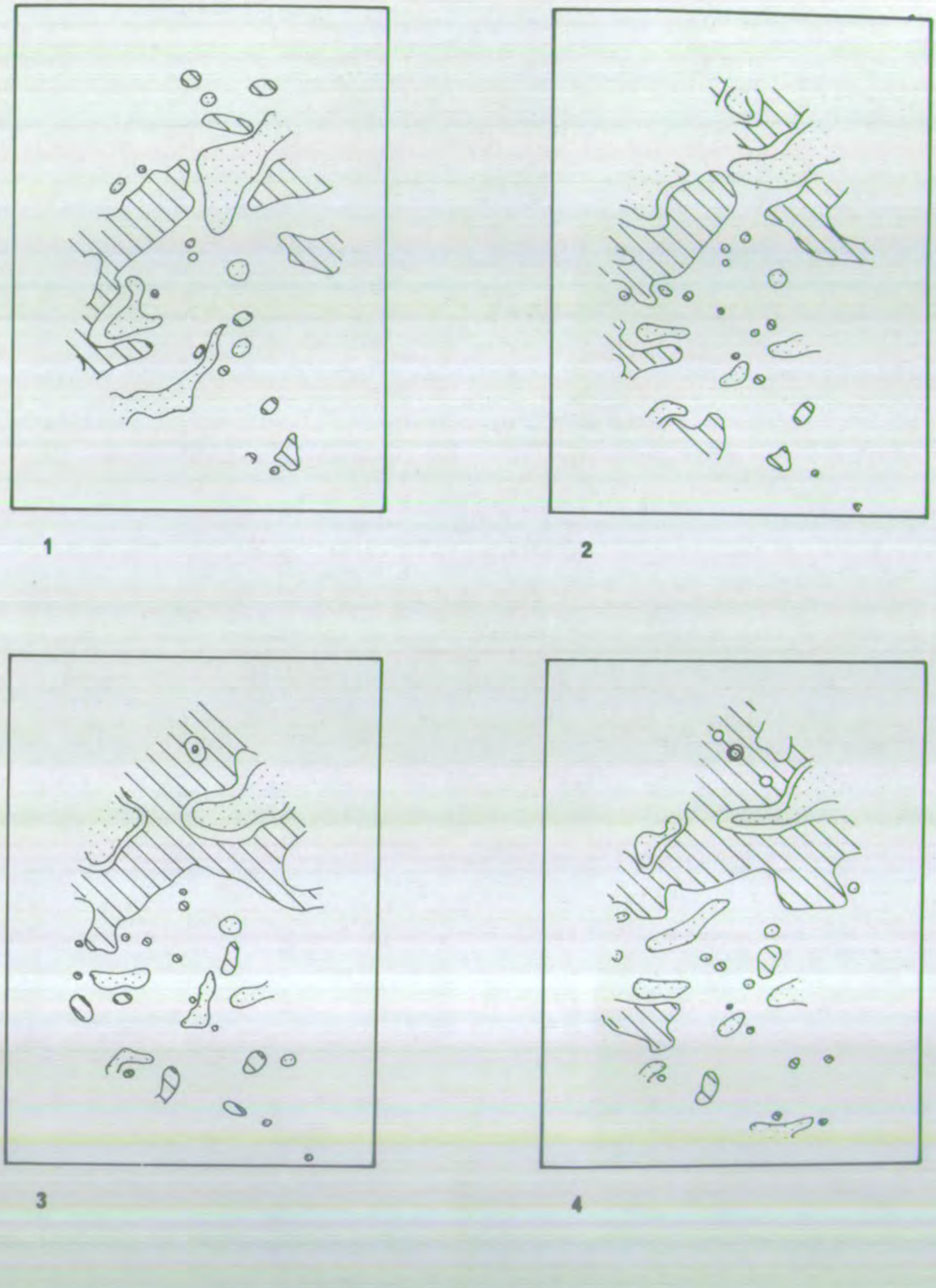


1 2 3 4

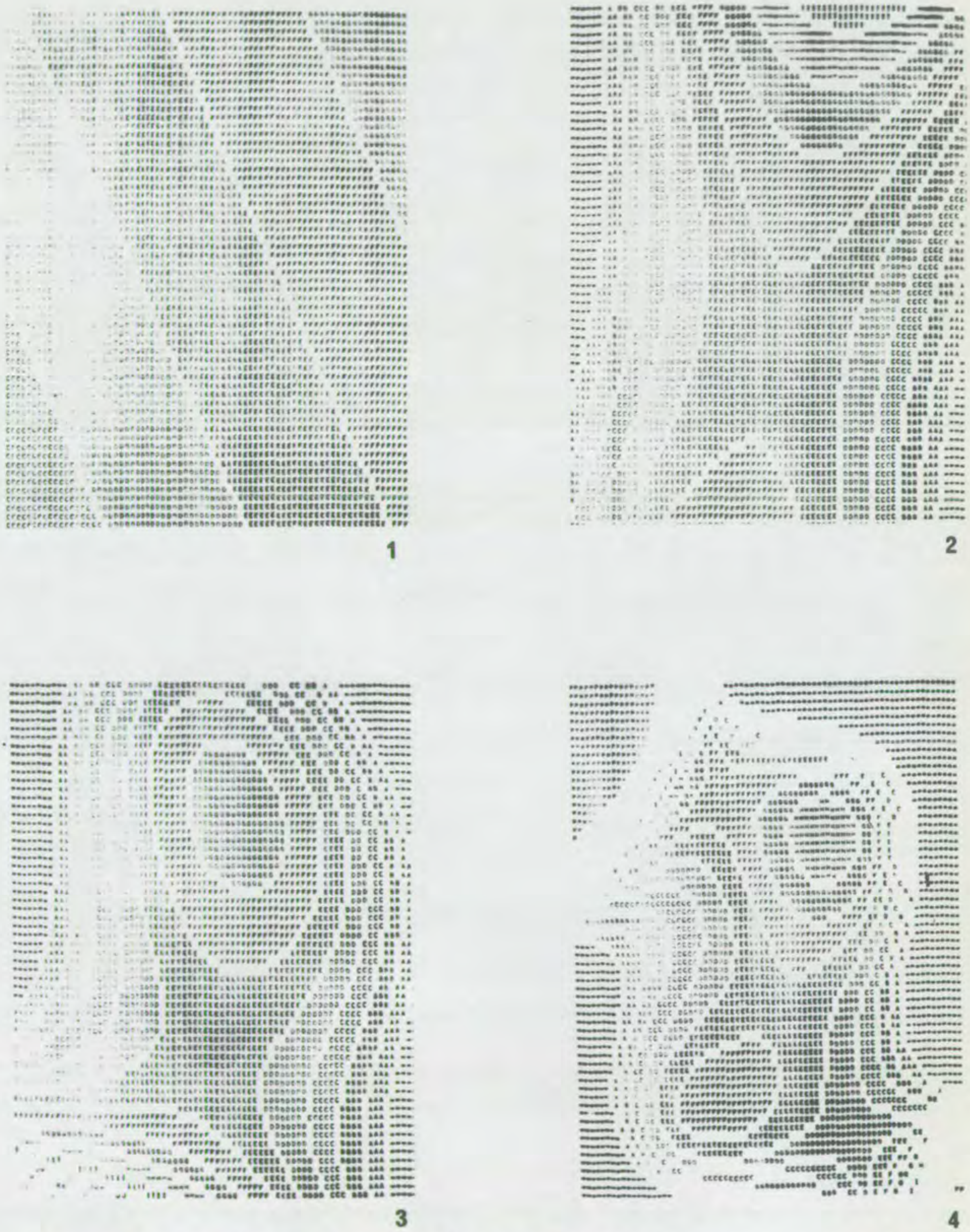
Figure(6.3.6b) Deviations from trend surfaces extracted from raw data (orders 1 to 4). Interval 5, Deep Soft to Roof Soft coal.
For key see figure(6.3.2b).



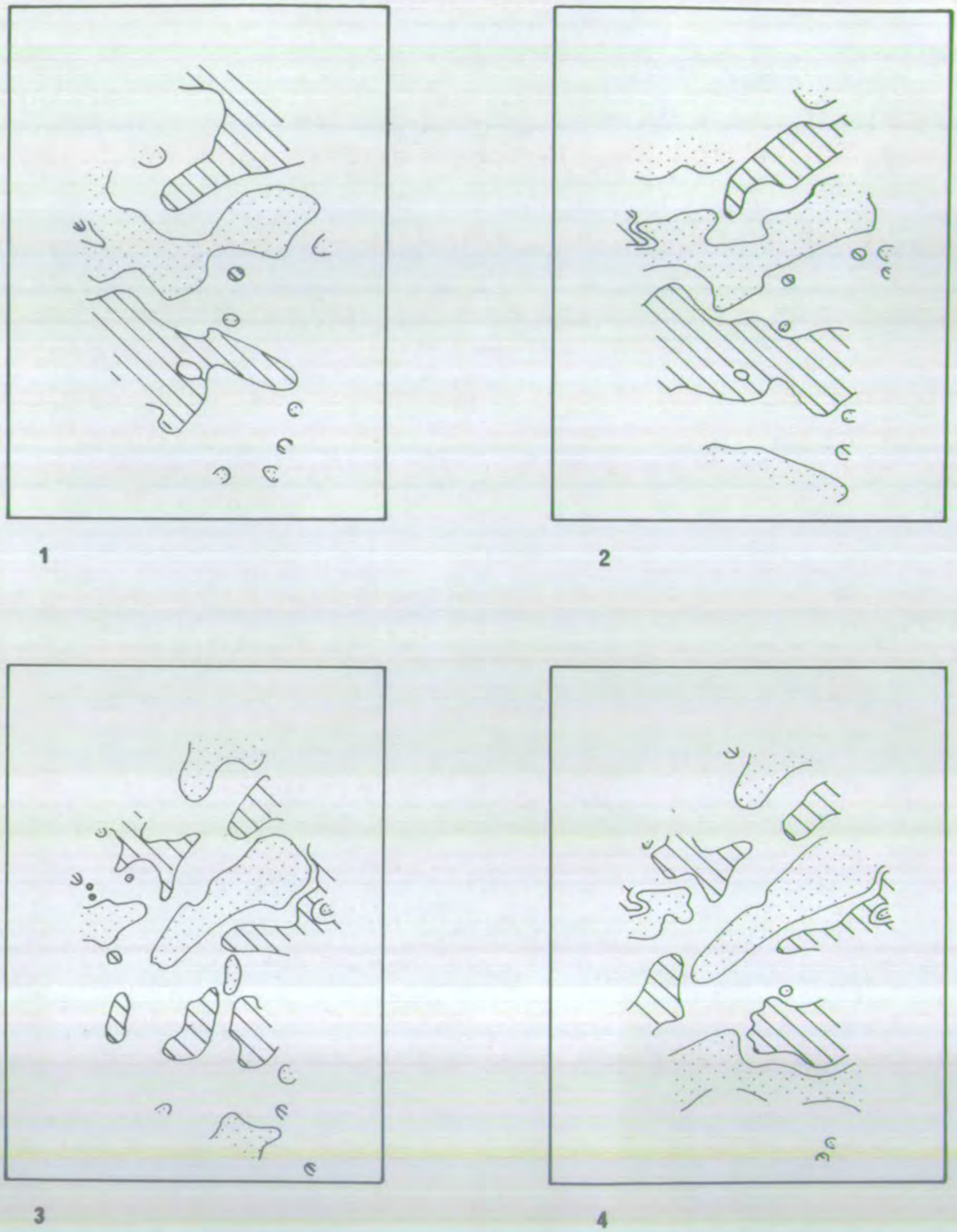
Figure(6.3.6a) Trend surfaces of order 1 to 4 ; raw data, total thickness of interval 5.



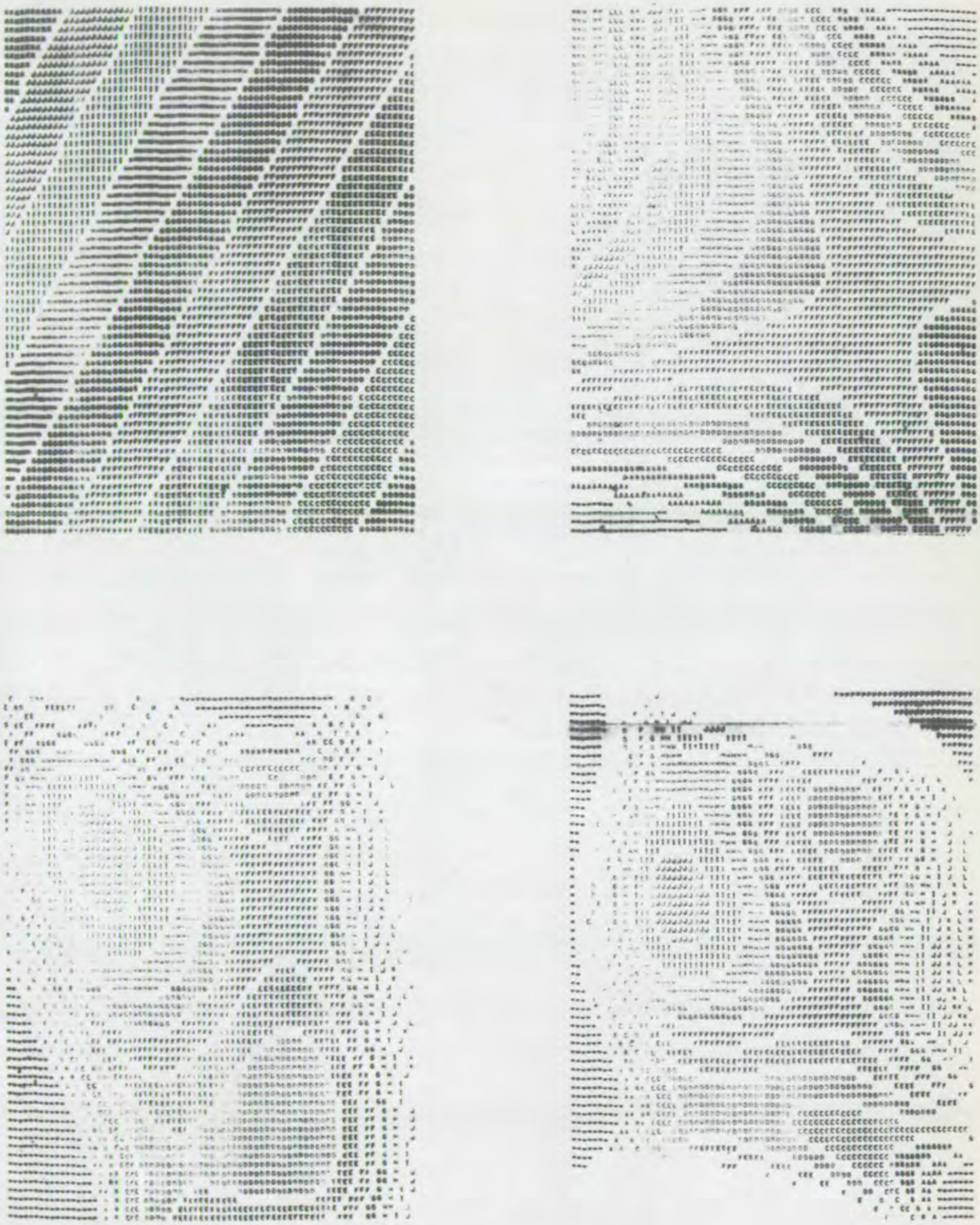
Figure(6.3.7b) Deviations from trend surfaces extracted from raw data (orders 1 to 4). Interval 6, Roof Soft to Chavery coal.
For key see figure(6.3.2b).



Figure(6.3.7a) Trend surfaces of order 1 to 4 ; raw data, total thickness of interval 6.



Figure(6.3.8b) Deviations from trend surfaces extracted from raw data (orders 1 to 4). Interval 7, Chavery coal to Clay Cross Marine Band. For key see figure(6.3.2b).



Figure(6.3.8a) Trend surfaces of order 1 to 4 ; raw data, total thickness of interval 7.

a) The contours on trend surfaces shown in figures(6.3.2a) to (6.3.8a), and (6.6.2) to (6.6.7) have the values :-

-	0	A	10	feet
	10	B	20	
	20	C	30	
	30	D	40	
	40	E	50	
	50	F	60	
	60	G	70	
	70	H	80	
	80	I	90	
	90	J	100	
	100	K	110	
	110	l	120	
	120	M	130	
	130	N	140	
	140	O	150	
	150	P	160	
	160	Q	170	
	170	R	180	
	180	S	190	
	190	T	200	U

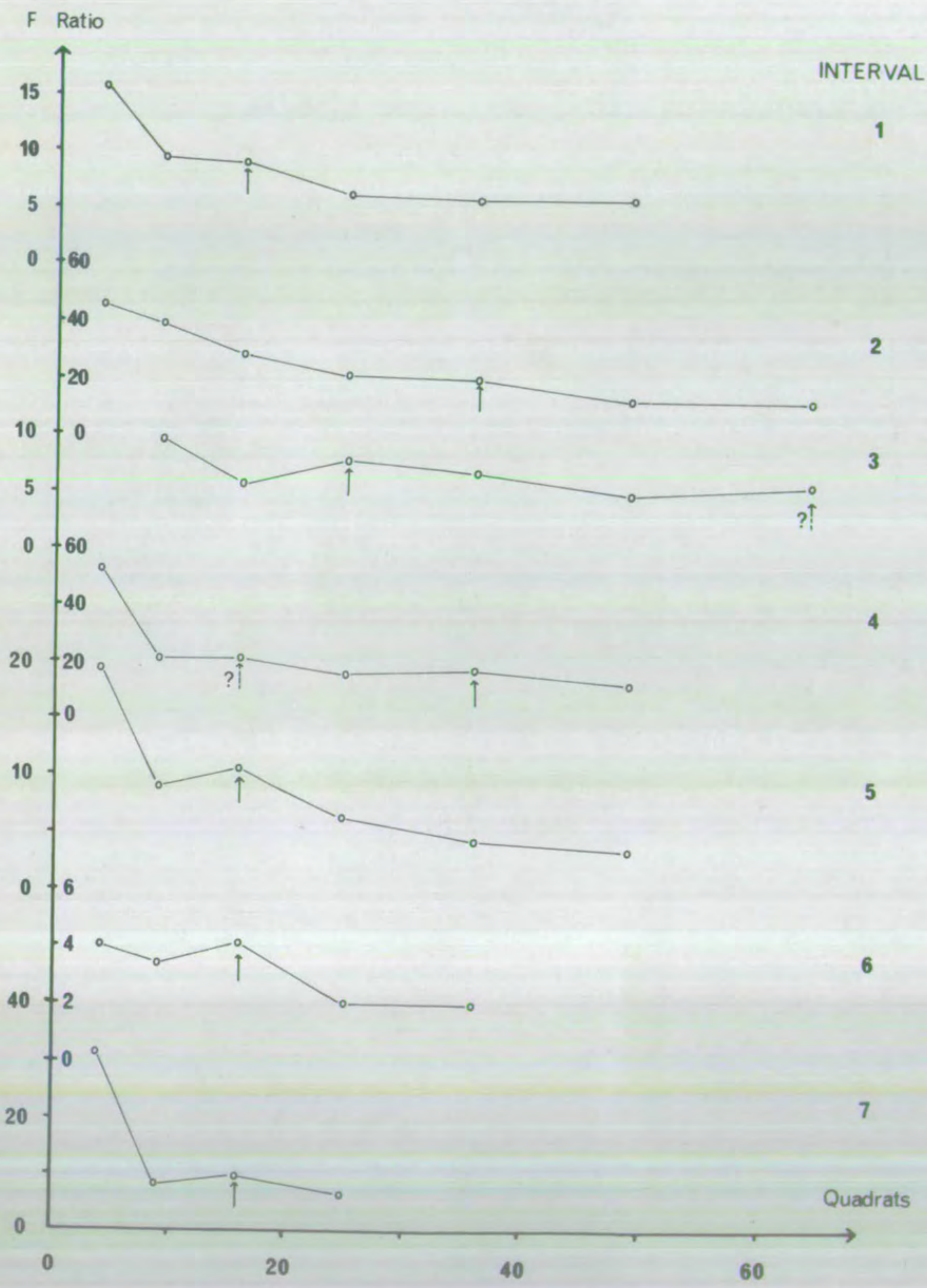
Figure(6.6.1) contours have the values :-

-	0	A	5	feet
	5	B	10	
	10	C	15	
	15	D	20	
	20	E	25	
	25	F	30	
	30	G	35	
	35	H	40	
	40	I	45	
	45	J	50	K

b) The margins of the trend surfaces which are parallel to the spine of the thesis are orientated North-South, with North towards the top of the page.

c) The trend surfaces refer to the area shown in figure(2.0.1). The scale is approximately 0.08 inches (0.2 cm.) to one mile.

Table(6.3.9) Information for the interpretation of trend surface and deviation maps ; East Midlands Coalfield.



Figure(6.4.1) F ratios for quadrat sizes.

6.4 Quadrat Size and Grid Samples

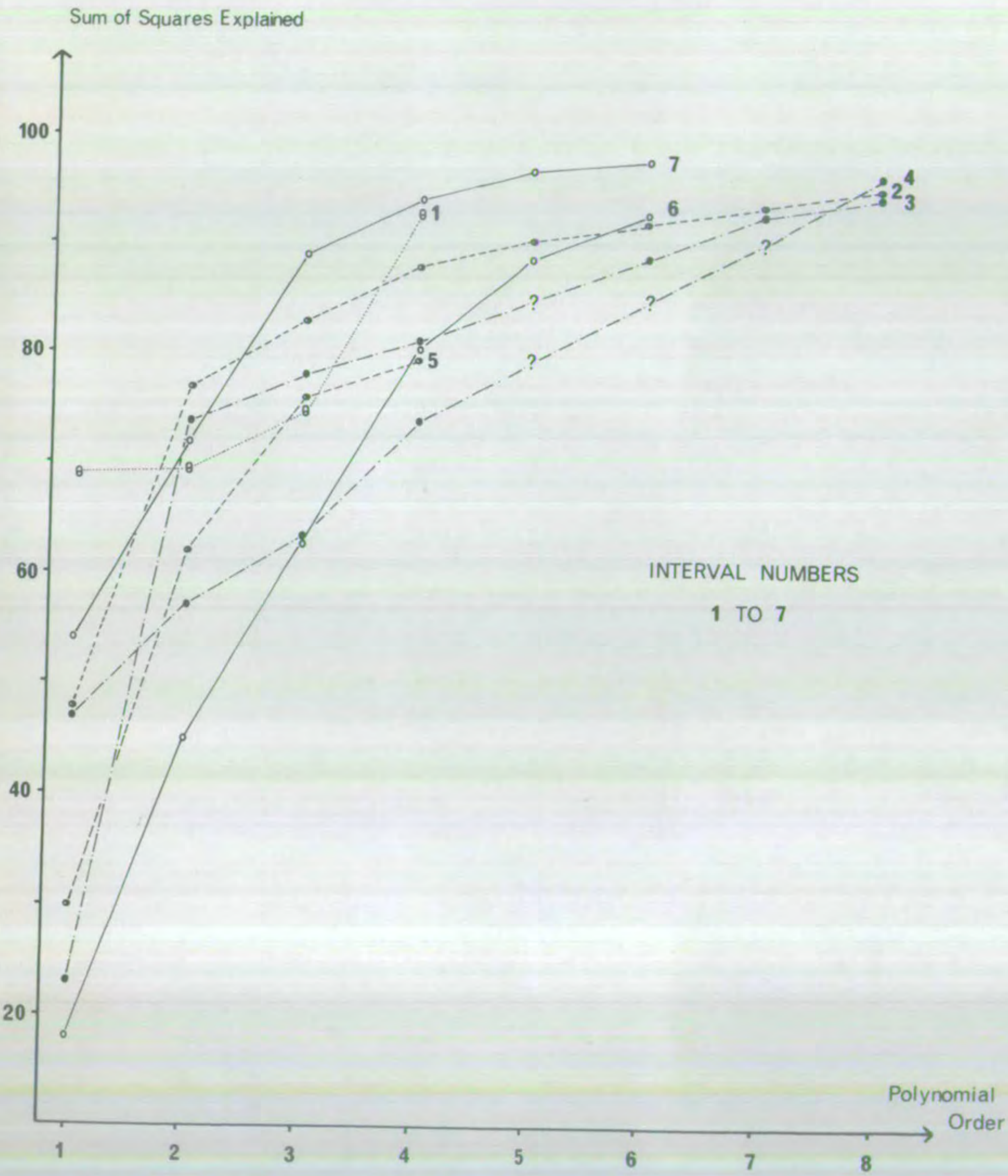
The seven data sets were scanned with quadrats of sizes decreasing to twice the mean area, and in each case the F ratio, of mean squares between-quadrats divided by mean squares within-quadrats, was computed. The results, shown in figure (6.4.1), are unambiguous except in the cases of intervals 3 and 4, where there were two peaks in the curves. The peaks corresponding to the smaller quadrats were chosen so that no interesting variability would be lost.

The results are consistent and can be readily interpreted. The intervals not containing thick sandstones have peaks at a quadrat size of about 1/16th of the map area or about 84 square miles. The presence of sandstones reduces the quadrat area to 38 square miles for intervals 2 and 4, and to 54 square miles in the case of interval 3. The scale of local processes of large magnitude is, therefore, reduced for thick but not for thin sandstones. If these two types are genetically related, then perhaps the accumulation of large thicknesses of sand distorts the sediment distribution pattern, rather than variations in this pattern giving rise to basically different sandstones. This important point is developed in section (8) where the sedimentology of the sandstone bodies is considered.

Using the quadrat sizes determined above, the data sets were scanned and geometrically averaged using an overlapping scheme. The sample sizes, including redundant quadrats, are listed in table (6.4.2). The gridded data produced were submitted to trend surface analysis.

Interval	Sample Quadrats	Redundant
Threequaters to Tupton coal	49	4
Tupton to Parkgate coal	121	8
Parkgate to Deep Hard coal	81	2
Deep Hard to Deep Soft coal	121	12
Deep Soft to Roof Soft coal	49	5
Roof Soft to Chavery coal	49	0
Chavery to Clay Cross Marine Band	49	1

Table(6.4.2) Sample sizes for gridded data.



Figure(6.5.1) "Fit" of trend surfaces extracted from gridded data.

6.5 Trend Surface Analysis of Gridded Data

The fits of the trend surfaces to the gridded data are presented in figure (6.5.1). They are notably higher, and the curves much more closely grouped, than those obtained from analysis of the raw data; figure (6.3.1). The grouping suggests that the noise in each subset of gridded data has been reduced to about the same level. This result vindicates the gridding technique.

All the surfaces with random deviations, described below, were of quartic or higher order. The lowest fit was 80% and all but this one were over 90%. The noise levels have thus been appreciably reduced so that the regional and large-scale components should be of sufficient magnitude to allow the analysis to succeed.

Large increases in explained variance between linear and quadratic surfaces for four intervals, suggest that large-scale controls operate with some symmetry within the map area. The remaining intervals, 1, 4, and 7, with regional controls of larger scale than the map, have linear surfaces which approximate Wills' (1956) isopachs. An interplay of basinal and more local downwarping is suggested.

The serial correlation coefficients are listed in table (6.5.2). Not all the selected surfaces have deviations which are strictly random in all directions, since it appears that the coefficient can increase with increasing polynomial complexity. The best approach to total randomness was used as a practical substitute.

Quartic surfaces reduced deviations to residuals in the case

Interval	Order	Serial Correlation Coefficients			
		E-W	N-S	NE-SW	NW-SE
1	1	+0.705	+0.005*		
	2	+0.698	-0.032*		
	3	+0.668	-0.059*		
	4	+0.107*	-0.144*		
2	1	+0.800	+0.636	+0.521	+0.538
	2	+0.685	+0.417	+0.226	+0.390
	3	+0.595	+0.265	+0.104	+0.226
	4	+0.481	+0.239	+0.059*	+0.258
	5	+0.403	+0.090*	-0.049*	+0.086*
	6	+0.384	+0.004*	-0.189*	+0.099*
	7	+0.290	-0.128*	-0.180*	-0.042*
	8	+0.116	-0.228*	-0.367*	+0.058*
3	1	+0.838	+0.456		
	2	+0.511	+0.282		
	3	+0.468	+0.245		
	4	+0.379	+0.115*		
	5				
	6	+0.285	-0.039*	+0.228	-0.375*
	7	+0.128	-0.107*	+0.099*	-0.348*
	8	+0.043*	-0.199*	+0.233	-0.450*
4	1	+0.652	+0.430		
	2	+0.523	+0.319		
	3	+0.424	+0.292		
	4	+0.379	+0.212		
	5				
	6				
	7				
	8	+0.039*	-0.258*	-0.148*	-0.257*
5	1	+0.533	+0.324		
	2	+0.375	+0.183		
	3	+0.198	+0.002*		
	4	+0.034*	-0+070*		
6	1	+0.509	+0.425	+0.482	-0.080*
	2	+0.382	+0.234	+0.293	-0.271*
	3	+0.316	+0.130*	+0.305	-0.485*
	4	+0.293	-0.216*	-0.012*	-0.492*
	5	+0.062*	-0.254*	+0.183	-0.509*
	6	-0.030*	-0.299*	+0.402	-0.610*
7	1	+0.692	+0.409	+0.192	+0.265
	2	+0.545	+0.287	-0.052*	-0.014*
	3	+0.377	+0.010*	-0.389*	-0.294*
	4	+0.235	-0.165*	-0.312*	-0.564*
	5	-0.447*	+0.051*	-0.256*	-0.383*
	6	-0.494*	+0.049*	-0.290*	-0.278*

Table(6.5.2) Serial correlation coefficients from gridded data : * indicates value less than 2 standard deviations greater than zero.

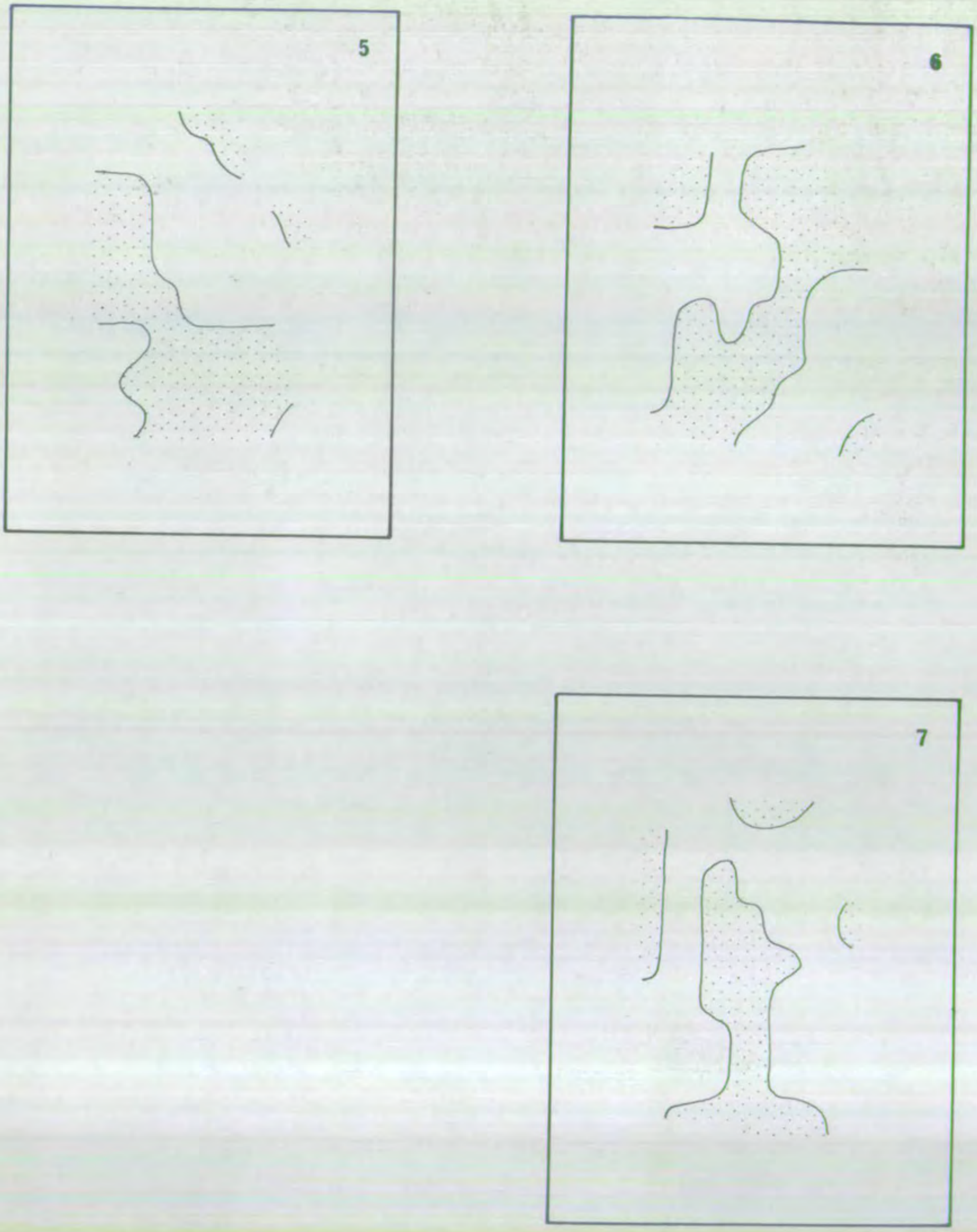
of intervals 1 and 5, while quintics were required for 6 and 7. The North-East to South-West coefficient for the interval 6 quintic (0.183) was only slightly higher than the critical value (0.160). An approximation was again made for interval 3 (a heptic surface) where the coefficient (0.128) exceeded the East-West limit (0.120), and interval 2 (an octic surface) where the same coefficient was high: 0.116 compared to 0.100.

In general the East-West and North-East to South-West coefficients are high and often the last to fall below the critical limits. Since an overlapping grid scheme was used, the coefficients show tendencies to elongation amongst the large-magnitude, larger-scale local components. The deviations, therefore, show patterns of elongation directed towards the East and North-East and the processes which formed them must operate across, rather than up and down, the palaeoslope.

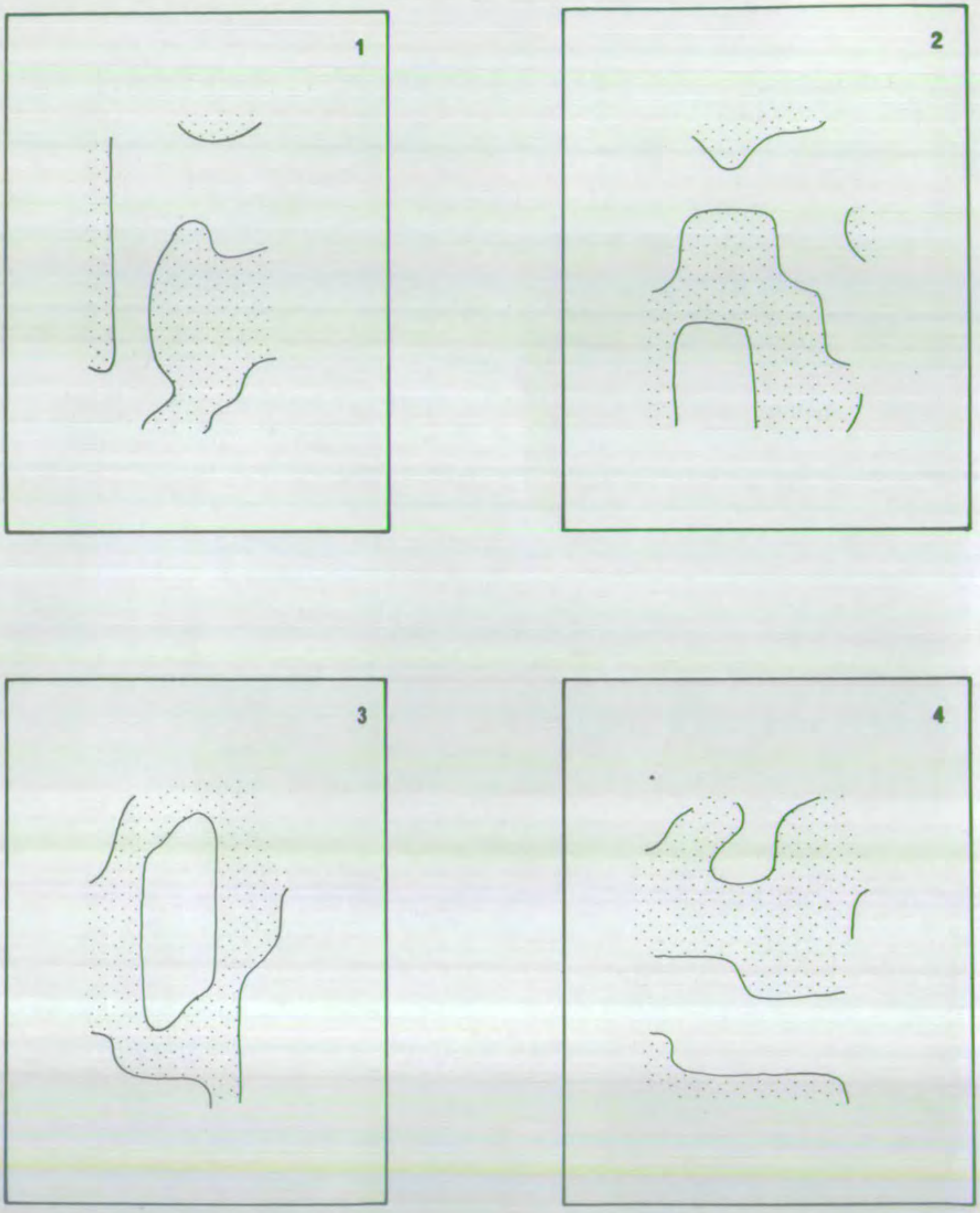
6.6 Separation of Regional from Local

The trend surfaces, which have random deviations, contain predominantly local and regional components and, therefore, include the interesting variability. Since the mean area of the gridded data set is larger than that of the raw data set, the random deviations, computed above, will contain components which can be considered local, if only very small-scale, with respect to the original data.

These surfaces were further analysed using trend surfaces.



Figure(6.6.8) Quadratic trend of trend deviations for intervals 5, 6 and 7.
stippled deviations positive
blank deviations negative (excluding map margin)



Figure(6.6.8) Quadratic trend of trend deviations for intervals
1 to 4.
stippled deviations positive
blank deviations negative (excluding map margin)

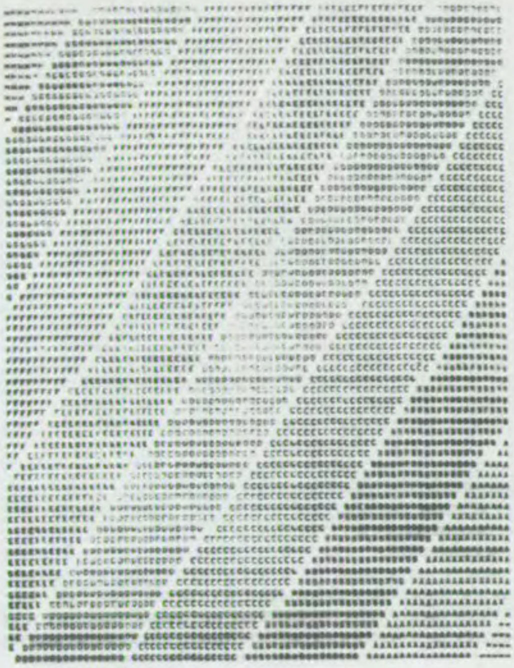
Since a standardised sample is required for comparison, the trend values for each surface over a 49-point grid were submitted as data for analysis. The trends of trends were computed only to cubic order because the purpose of the exercise was to produce an estimate of the regional component. While the final surfaces do not always differ greatly from equivalent orders of their predecessors, they permit quantification of the moderate and large-scale local components. The surfaces are displayed in figures (6.6.1) to (6.6.7).

As discussed in section (5), there is no logical statistical method of selecting the trend which separates regional from local. In this case it was decided to use the quadratic trends, for three reasons:-

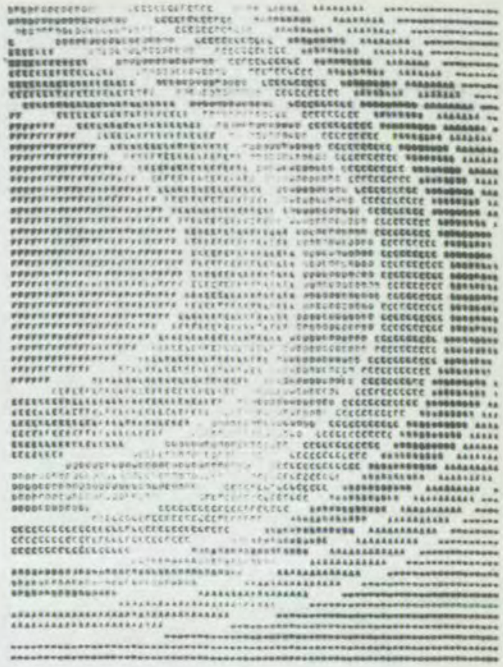
1. The contours on the palaeoslope suggested by Wills (1956) are curved and could not be produced by a linear surface;
2. Some linear surfaces, notably for interval 5, are strongly affected by local components, so that other trends in the data are omitted;
3. Some cubic surfaces contain moderate-scale local components.

The quadratic surfaces show some similarities to those extracted from the raw data. The deviation maps, figure (6.6.8), are, however, quite different.

The interpretive value of the trend surfaces and deviation maps in terms of the underlying geology is suspect. As mentioned before the problem arises that while some sandstones are incorporated within the trends others are left as deviations; interval 4, figure (6.6.4), can be taken as an example. Presumably, diagnosis with the aid of trend analysis can only be done with confidence where the geology is thoroughly understood beforehand. It is not surprising that it has been argued



L

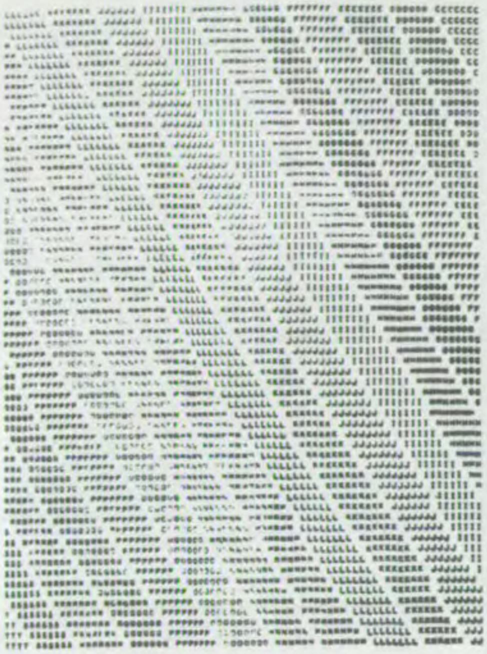


Q

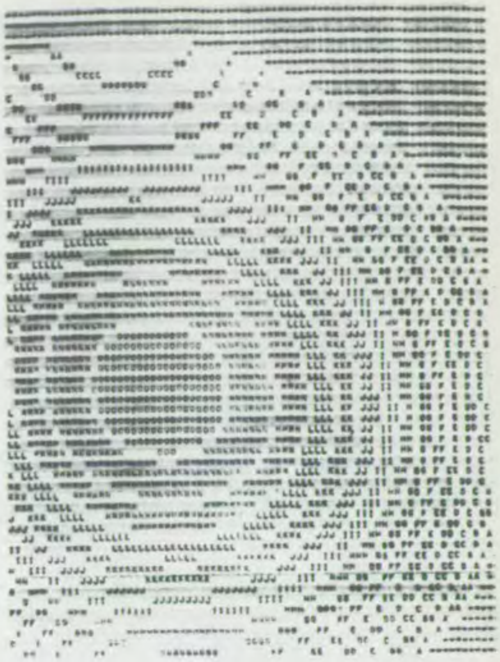
Linear (L), Quadratic (Q)
and Cubic (C) trend of
trend surfaces.
Interval 1

C

Figure(6.6.1)



L

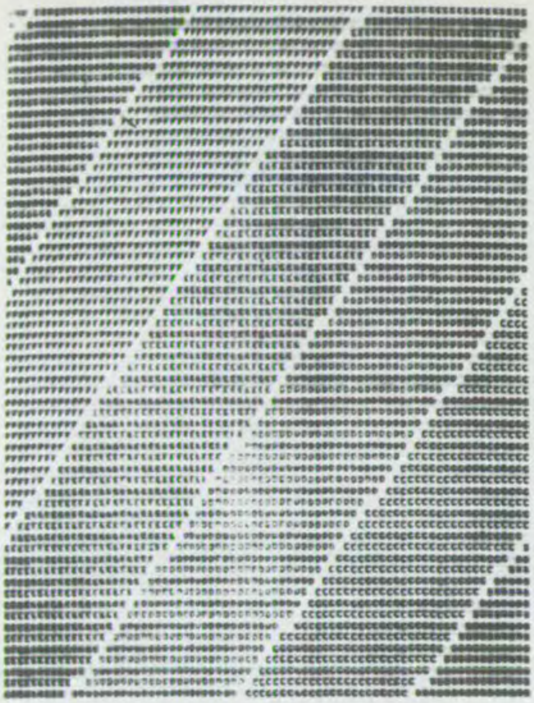


Q

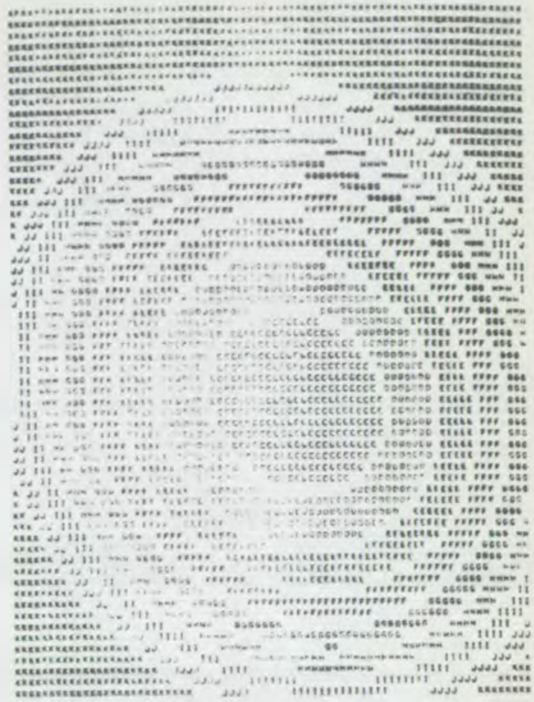
Linear (L), quadratic (Q) and cubic (C) trend of trend surfaces.
Interval 2.

C

Figure(6.6.2)



L



Q

Linear (L), quadratic (Q) and cubic (C) trend of trend surfaces. Interval 3.

C

Figure(6.6.3)

L

Q

Linear (L), quadratic (Q) and cubic (C) trend of trend surfaces.
Interval 4.

C

Figure(6.6.4)

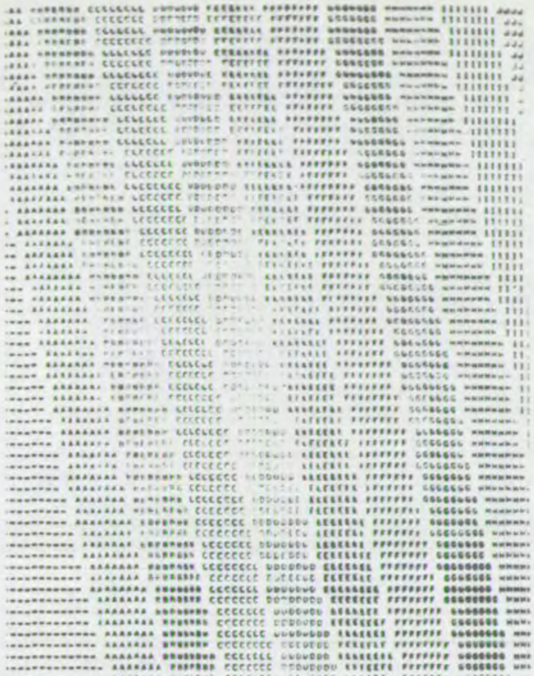
L

Q

C

Linear (L), quadratic (Q) and cubic (C) trend of trend surfaces.
Interval 5.

Figure(6.6.5)



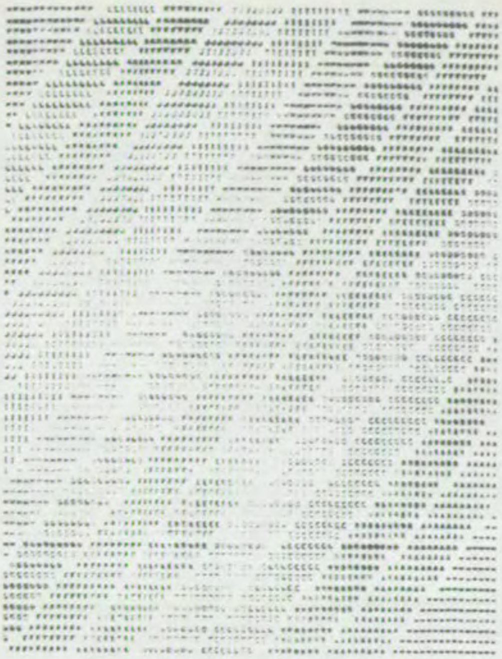
L

Q

C

Linear (L), quadratic (Q) and cubic (C) trend of trend surfaces.
Interval 6.

Figure(6.6.6)



L

Q

C

Linear (L), quadratic (Q) and cubic (C) trend of trend surfaces. Interval 7.

Figure(6.6.7)

that the technique cannot produce answers which could not have been obtained from the raw data (Lee and Middleton 1967).

Disregarding interpretive problems, we are now in a position to weigh statistically the inferences obtained from a study of the raw isopachs.

6.7 Comparisons of Intervals

Bearing in mind the criticisms mentioned in section (5.3), correlation coefficients were used to compare trend surfaces and deviations, because no alternative technique was available which measures the degree of similarity as well as dissimilarity.

Trend surfaces are composed of simple flexures, so that if the trend value at any given point is high, relative to the mean, it is likely that its immediate neighbours will also have high trend values. In other words, the trend surface is autocorrelated. Comparison of two trend surfaces by means of the correlation coefficient computed from point samples, is, in effect, equivalent to the measurement of the relative positioning of the highs and lows of the two surfaces. Fortunately, this is precisely what is required in this instance. However, when the highs and lows of the two surfaces coincide (a strong positive correlation) the correlation coefficient will be numerically greater than actually warranted, because of the effect of pairing of high and low values. This situation is analogous to the nonsense correlations which arise between time-related variables (Yule and Kendall 1958, p.319) and perhaps the invention of some three-dimensional variate-differences technique is required.

Where a correlation of reasonable strength exists between two surfaces, the subtraction of the smooth trend values from the raw data will magnify the correlation between deviations, especially in the situation where the local components are moderately strong.

To the knowledge of the author, no attempt has yet been made to measure the distortion of the correlation coefficient arising in this way. It is more likely that changes in value rather than sign are involved, so that the results discussed below are probably valid although the significance levels may be totally meaningless. The actual coefficients are listed in table (6.7.1).

Significant correlations between trends show that the processes giving rise to interaction arise on the regional scale. The sequence of trend correlations has a simple pattern; weak positive correlations are followed by strong negative correlations which decrease in magnitude. A positive result suggests that adjacent intervals have coincident thickness maxima, whereas a negative result suggests the coincidence of maximum and minimum values.

The weak positive correlation between the trends of intervals 1 and 2 infers that they may have been emplaced by the same mechanism, possibly downwarping with its acme within the map area. However, the shift of the locus of maximum thickness to the East causes the reduction of the coefficient to insignificance. Intervals 2 and 3 have a significant negative correlation, and it follows that the subsidence pattern must have altered completely if the result is to be interpreted in these terms.

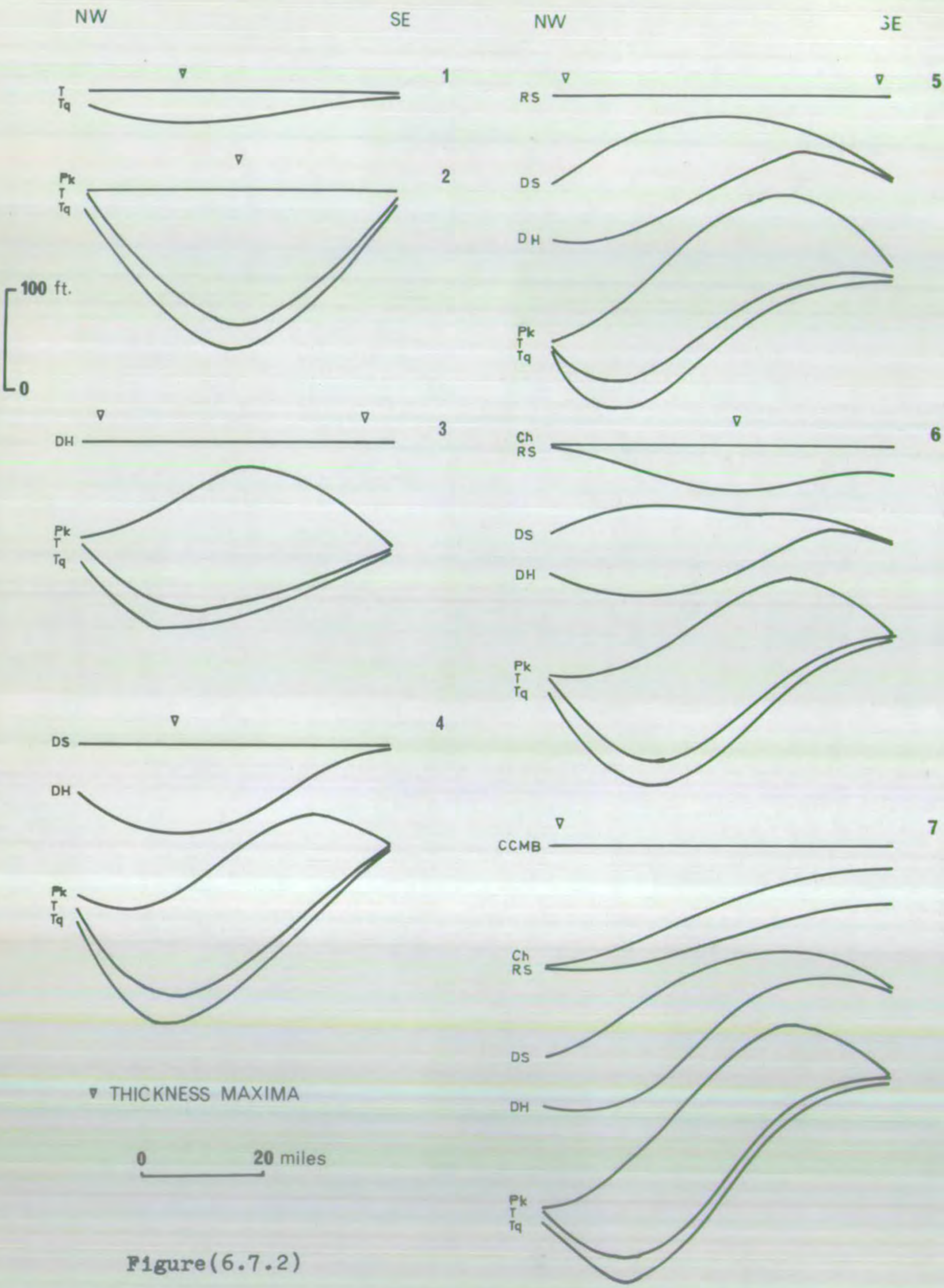
Intervals	Correlation between trends	Correlation between deviations
1 vvs 2	0.10	$0.37^{@@}$
2 vvs 3	$-0.82^{@@@}$	-0.16
3 vvs 4	-0.12	-0.06
4 vvs 5	$0.30^{@}$	-0.26
5 vvs 6	$-0.86^{@@@}$	$-0.29^{@}$
6 vvs 7	$-0.59^{@@@}$	$-0.43^{@@}$

Table(6.7.1) Comparative correlation coefficients for adjacent intervals ; quadratic trends of trends and associated deviations.

@ coefficient significant at 5% level

@@ coefficient significant at 1% level

@@@ coefficient significant at 0.1% level


NW
SE
NW
SE
1
T
Tq
2
Pk
T
Tq
100 ft.
0
3
DH
Pk
T
Tq
4
DS
DH
Pk
T
Tq
5
RS
DS
DH
Pk
T
Tq
6
Ch
RS
DS
DH
Pk
T
Tq
7
CCMB
Ch
RS
DS
DH
Pk
T
Tq
THICKNESS MAXIMA
0
20 miles

Figure(6.7.2)

Presumably, if the Parkgate coal was approximately at mean "sea" level over the whole area throughout its formation, it is necessary to postulate the onset of renewed subsidence everywhere except where it was previously most intense. Even more extraordinary is that the locus of maximum subsidence must return to the position held for interval 2, to emplace interval 4, if subsidence is held to be the sole regional control. Figure (6.7.2) shows sections drawn down the palaeodip and illustrates the shifting patterns of subsidence. The sections are in some cases distorted and reference should be made to the trend surfaces themselves.

The positive correlation between intervals 4 and 5, not seen in figure (6.7.2), initiates a second sequence analogous to that described above.

This interpretation in terms of pure subsidence appears too artificial to be acceptable. However, there is at least one other possible explanation. This analysis has been carried out using the thicknesses of the intervals as they now stand. Obviously, extensive compaction has occurred since the time of deposition, when the processes we are seeking were operative. Commonly, but not ubiquitously, thick sandstones occur where the enclosing interval is thickest. Sandstones compact considerably less than organic and argillaceous deposits from their original states and, therefore, differential compaction may be a possible mechanism.

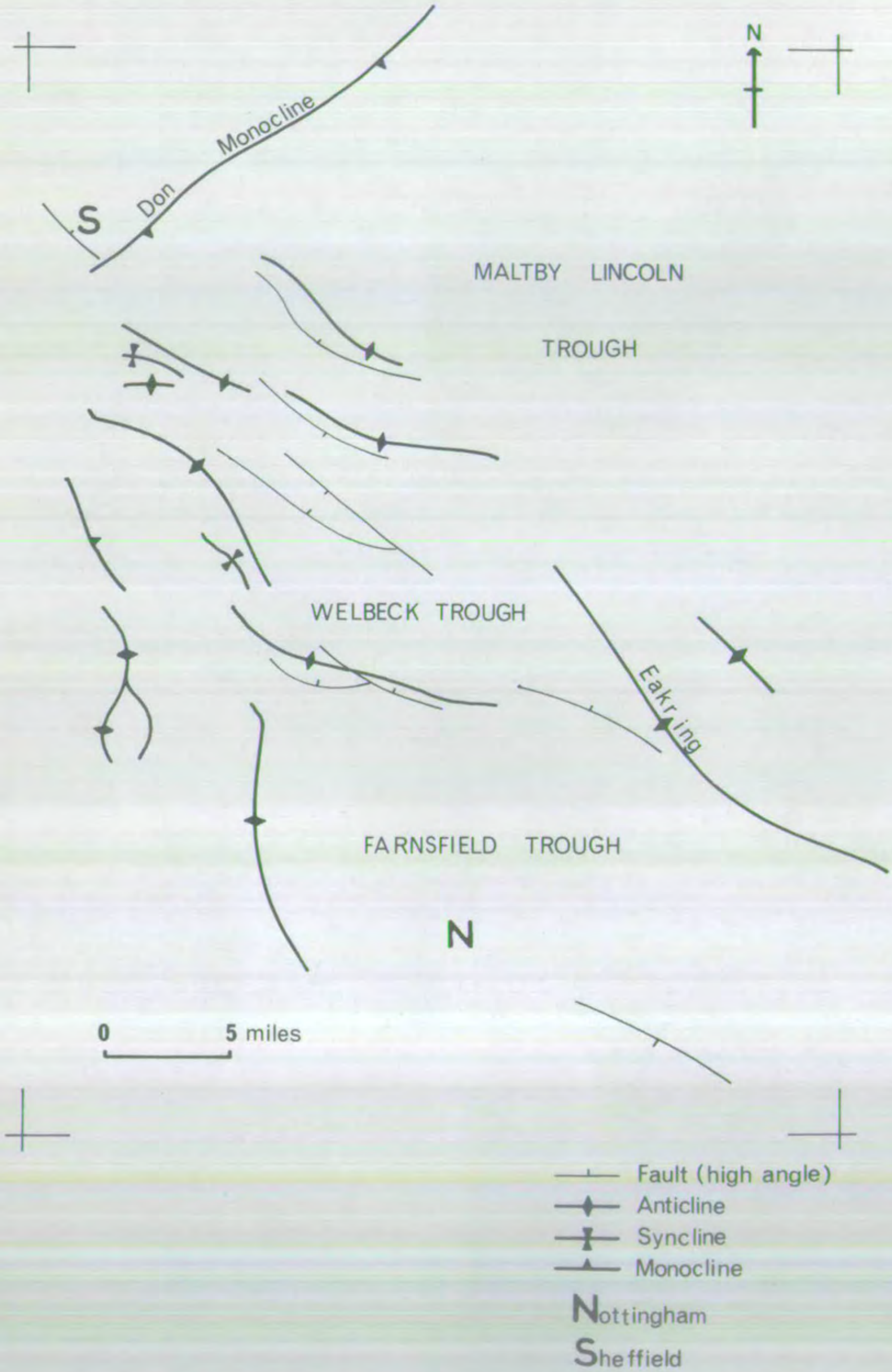
Differential compaction has, of course, been recognised before as a control on sedimentation but it is not generally held that its effect can be seen on the regional scale. However, Edmunds (1968) has recently proposed just this mechanism. He stated that "local and even more regional topographic irregularities are filled (temporarily) by thick deposits of plant material and clay sediment. Their strong compactibility, however, will allow later sediments to be deposited in the same low." Even setting aside the unwelcome concept of topographic irregularities, this mechanism can be adapted to explain the trend coefficients.

The present thin parts of the intervals are predominantly argillaceous and presumably, therefore, originally much thicker, and possibly as thick as the sandstone bodies. Compaction in the argillaceous zones, being much greater than in the sandy areas, will permit the accumulation of much greater thicknesses of sediment of the subsequent interval. As noted in section (4) the coals tend to thin over thick sandstones and, therefore, greater thicknesses of potentially very compactible peat will accentuate the inheritance effect of the compaction of clay.

By means of this mechanism negative correlations could arise without localised subsidence, although this is still required to explain direct proportionality.

The correlations between deviations can be considered in a similar way. All the negative trend coefficients have corresponding negative correlations between deviations, implying that the same mechanism may be operative simultaneously on different scales. While it is not impossible that regional or basinal downwarping and local, possibly tectonic, subsidence could proceed in unison, the necessity of invoking perfect inversions of the subsidence pattern, on all scales, is unwelcome because the hypothesis is both complex and artificial. However, there appears to be no reason for assuming that differential compaction does not operate on all scales at the same time.

The negative correlation between deviations for intervals 4 and



Figure(6.7.3) Structure.

5, where the trends have a positive correlation, suggests that although the regional control may be taken over by the stronger effects of basinal downwarping, differential compaction continues to operate effectively on a smaller scale. However, it is now difficult to explain the twin positive correlations for intervals 1 and 2, even though the effects of differential compaction would be minimised, or even nullified, by the virtual lithological homogeneity of interval 1.

To summarise, it is much simpler to interpret the similarities and differences between intervals in terms of regional or basinal downwarping, with the possible superimposition of eustatic rises in "sea" level, and differential compaction, than in terms of pure subsidence. This model has been suggested previously. For example, Duff and Walton (1964) stated that "The thickness of a sedimentary succession is a function of regional subsidence and compactional effects", although they added that local tectonic contributions could not be ignored. These results provide some concrete evidence in support of this model.

Although tectonic control cannot be disproved, it can be shown that the pre-Permian structural features in the Westphalian rocks do not have any expression in the sedimentary patterns under consideration. The autocorrelation coefficients clearly show that the elongation of local highs and lows among the deviations are directed towards the East and North-East, and, therefore, are almost orthogonal to the predominant structural trend towards the North-West; figure (6.7.3). Furthermore, the highs and lows straddle the fold axes and faults and are not exclusively associated with the structural troughs.

Although the elongate patterns of highs and lows amongst the deviations can probably be passed on by differential compaction, they must be initiated by some other process. Since the pre-Permian tectonic movements must be rejected, the only remaining credible alternatives are localised downwarping and sedimentation. In the former case it is difficult to explain why a positive correlation was not obtained between deviations for intervals 4 and 5, where the trend coefficient clearly shows that the basin was in an unstable state. Sedimentation and compaction provide a simpler and less ambiguous explanation but further discussion of the mechanism is deferred to sections (7 and 8),where the sandstones, the key to the sedimentological system are examined in detail.

However, it is informative to consider, at this point, how the sandstones fit into the model. The negative trend correlations between intervals 2, 3 and 4 are associated with offset between adjacent sandstone bodies, section (4). The positive correlation between intervals 4 and 5 occurs where sandstone thickness maxima coincide, and yet the Deep Soft Rock is located marginally to the zone of maximum thickness of interval 5. It follows that the location of the Deep Soft Rock was controlled by some mechanism operating on a scale much less than that controlling the positive correlation between intervals.

6.8 Conclusions

The observed interactions of juxtaposed intervals have been shown to be statistically sound, and the contribution from different scales has been measured. Positive correlations are generally weak and only marginally significant; they probably arise where large or small scale subsidence outweighs other processes. Negative correlations tend to have higher significance levels; although they can be interpreted in terms of a shifting pattern of subsidence a model based upon differential compaction in addition to regional downwarping is more acceptable.

A partial depositional model can be built upon these results. The processes involved are listed below.

1. Regional or basinal downwarping, alone or in combination with eustatic rises in "sea" level, probably operated continuously during the deposition of the seven intervals. Occasionally, the restriction of the location of maximum subsidence to within the map area, or perhaps simply an increase of the instability of the basement, caused this control to outweigh all others. Small-scale subsidence probably played a minor role in shaping the development of the Coal Measures sequences. Although it is impossible to prove that any small-scale subsidence that did occur was not related to tectonic forces, it has been shown that the pre-Permian structural movements did not have expression in this part of the Coal Measures.

2. When not outweighed by regional subsidence, differential compaction partially controlled sedimentation on the regional, local and smaller scales.

3. The sedimentation system operated on the local scale. There is a suggestion that local components (often associated with sandstones) of one interval can affect those of its successor, and that there may be some link between the process giving rise to negative deviation correlations and the mechanism of deposition of the sandstones.

Other controls, not discussed in this section, also influence sedimentation. The possible effect of peat thickness is discussed in sections (7) and (8), but other botanical factors are outwith the scope of this study.

COMPACTION

7.1 Introduction

In the conclusion to section (6) it was found that the variations in thickness of the Coal Measures rocks could most simply be interpreted in terms of regional subsidence and differential compaction. In this section an attempt is made to estimate whether compaction could produce the similarities and differences discovered on comparison of adjacent intervals. In order to maintain the objectivity of the conclusions of section (6), simulation of compaction has been produced using a deterministic model.

Prompted by the continuing search for oil, compaction in rocks has been studied almost as a by-product of the investigation of the variation of porosity and permeability with depth. Notable papers have been produced by Athy (1930), Hedburg (1936) and, more recently, Conybeare (1967). Jones (1939, 1944), Prozorovich (1964), Edmunds (1968) and Meade (1968) have also made important contributions. Most of the previous work on compaction in sedimentary rocks has been summarised by Weller (1959), Meade (1966) and Muller (1967).

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At the other end of the scale, there has been a lot of recent work done on the water content of recent sediments, and its variation with depth (see Richards 1967). Recent experimental work (Chilingar _et al_ 1968, Einsele 1967) has supplemented earlier information derived from soil mechanics (Terzaghi _et al_ 1967, Skempton 1944, 1953). Much of the previous work on the diagenesis of coal has been summarised by Teichmuller _et al_ (1967). In order to study the effects of compaction in the section of Coal Measures strata selected, it is necessary to study porosity conditions down to depths of about 500 feet. The model thus, of necessity, bridges the dichotomy in the previous work.

No great claims can be made for the accuracy of any simulation of compaction, and in this case the objective was simply an estimate of the effect of compaction as a control in the development of Coal Measures sequences. The sources of error are many and diverse. Principally, it is impossible to derive models for the compaction of every rock of different grain size and composition, for practical reasons. In addition, the projection from rock description to original sediment is open to gross errors, as mentioned in section (2). It was, therefore, decided to reconstruct the Coal Measures sediments using four end members, clay, silt, sand and peat. Mixtures of these members, whether as laminations or on the granular scale, cannot be handled by such a scheme, and rocks of this type were simply categorised according to the most dominant component.

Errors are permissible where their sense and magnitude are known, but the interplay of unknown sources could lead to a situation where any results would be totally uninterpretable. To avoid this problem all estimates and assumptions have been made so as to amplify the effect of compaction, and especially differential compaction.

7.2 Compaction Model

Technically, compaction can be simulated in a continuous or discrete fashion. A complete solution can be obtained by differential calculus (Gibson 1958) but a discrete model is more adaptable, and easier to handle and programme on a digital computer.

In the discrete model employed, Coal Measures rocks were uncompacted to packages in the state in which it is considered the rocks were deposited. The packages are then piled up, to simulate sedimentation, and their volumes continuously reduced on burial, to simulate compaction. The model can be switched off at any point so that various thicknesses of sediment, at compactional equilibrium, can be measured.

The size of the packages is critical. Obviously, for geological purposes, the smaller the packages, or increments, the better, but minimum limits were dictated by the size of computer available (16k) and the thickness of the section under consideration. A balance was struck using an increment of one foot (30.48 cm.) in length, which involves rounding errors of 0.5 feet, or a matter of a few inches in the original data. For convenience, the vertical sections of strata were considered to consist of boreholes of 1 cm^2 cross sectional area.

7.2(a) Compaction of clay

To what state should the Westphalian shales and mudstones be uncompacted? The common occurrence of mussels orientated parallel to the bedding plane suggests that reworking of the sediment by the depositing medium was extensive. Removal of the cover leaves sediment at the surface which is apparently in an overcompacted state. Uncompaction, therefore, should be to a stable state, some depth below the surface of the sediment pile. However, if too great a depth is chosen the model will be too unrealistic.

Fortunately, experimental work (Einsele 1967) has shown that clays (in this case artificially deposited kaolinite) are stable at a depth of about 30 cm. to current velocities, of the order of 30 cm/sec., which are fairly rapid. Although the Westphalian shales have a different mineralogy (Nichols et al 1960, 1962), the experimental data have been accepted as a first approximation.

The water contents of lake and sea bottom clays range from 85% to 327% of dry weight (Muller 1967). The principal control appears to be the sand and silt content of the clay, but Meade (1963) has suggested that the clay mineralogy, the presence of electrolyte solutions and exchangeable cations in the clay lattices, and the sedimentation rate are important factors. In addition, the water content is proportional to the amount of organic material in the clay (Sheppard et al 1955). This, and other recent work (e.g. Emery 1960, Richards 1962) has discredited the earlier view that clays are deposited with water contents approaching their liquid, or upper Atterberg, limit.

It is impossible, therefore, to quote a representative water content for clay 30 cm. below the sediment surface, and a high estimate (200% of dry weight) was made, which has the effect of overestimating the amount of compaction. In view of the presumably large amount of available vegetable matter in the Westphalian, it is possible that the clays originally had a moderate or high organic content. Surprisingly, Nichols et al (1960) found that the present organic carbon contents of the shales are not above average although concentrations in marine shales are much higher (Broadhurst 1958). The proposed water content, therefore, may not be grossly excessive.

Boswell (1960) gave an estimate of the water content of Carboniferous shale of 13%. This figure is high compared to a more recent average from the East Midlands Coalfield of 1.6% (Skipsey 1968, written communication) and a single measurement of 0.86% from the same area (Pritchard 1968, written communication). Consequently, a value of 1.5% was used as a first approximation to the average water content of saturated Westphalian shales.

Provided the system can be considered to consist of only solid and liquid phases, between the initial and present states, and the volume reduction is directly related to decreasing water content, the values selected above can be substituted into the relationship shown in appendix (10.2), to give a compaction ratio of approximately 6:1. This ratio has also been proposed by Ferguson (1963) from a study of crushed specimens of Crurithyris urei (Fleming). Thicknesses of Carboniferous shale were, therefore, multiplied by 6 to obtain the number of increments to be added during the sedimentation stage of simulation.

On burial, the volume of each increment is reduced, through a loss of its interstitial water, under the influence of the overburden pressure. The reduction is initially very pronounced but tails off as the permeability decreases (Muller 1967). However, Rittenberg <u>et al</u>

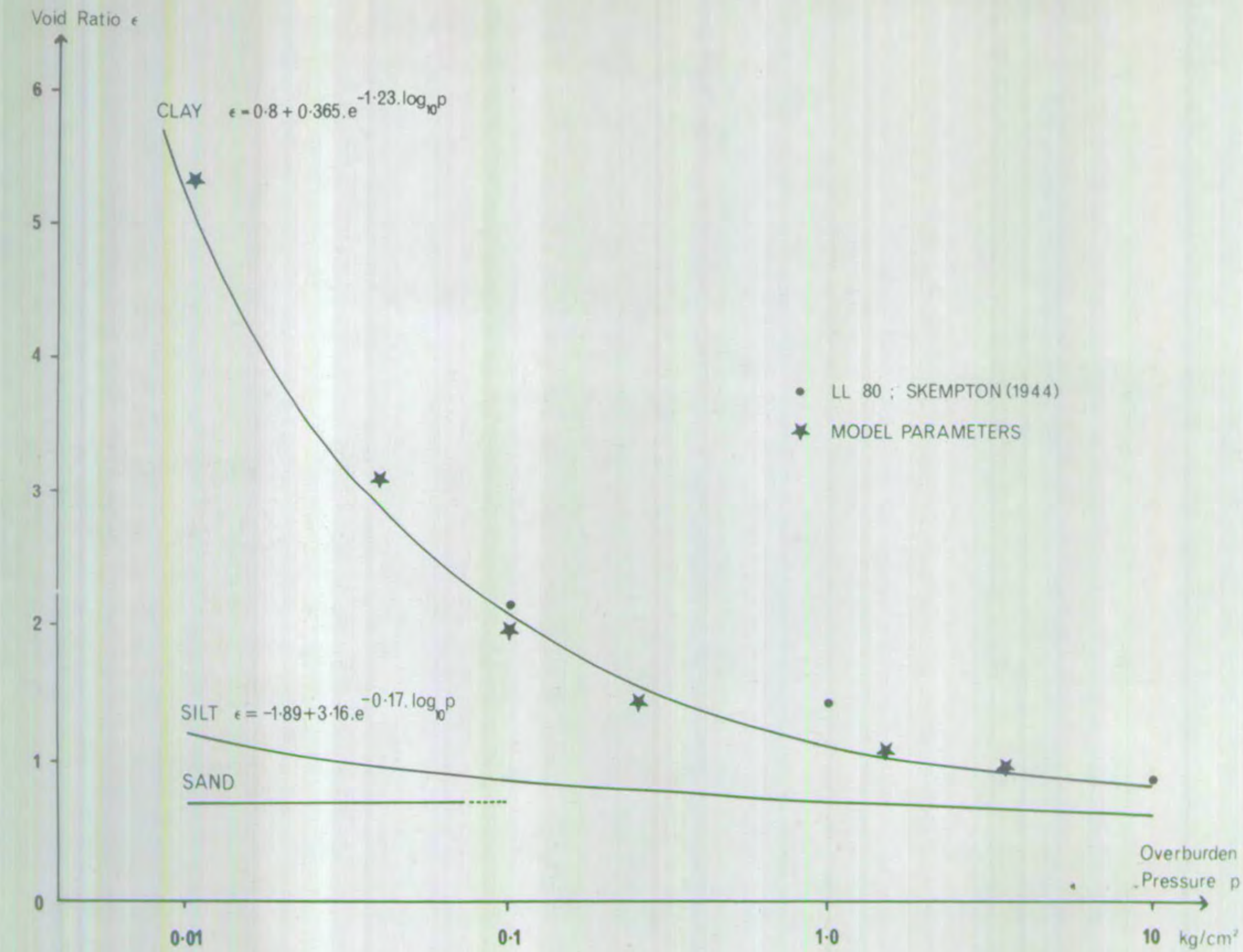
(1963)found a non-systematic reduction in water content with depth of burial. This effect may partly be a result of cementation and authigenic growth (Ho et al 1969) but could also arise from the lithological variations in the examined cores. The suggestion made by Shepard et al (1955) that, "... the water content remains constant but is using a larger per cent of the available total porosity.... ", was based on fluctuations in the water content with depth, which probably reflect only the fluctuations in the clay per-cent of the total sediment. Skempton (1944) has shown that there is a good linear correlation between the per-cent clay fraction and the void ratio and, therefore, water content of a saturated sediment. The possibility of undersaturation arising from the production of a gaseous phase (Shepard et al 1955) cannot be entertained by the present simulation, but the evidence, for the occurrence of this phenomenon to such an extent as to cause distortion, has been shown to be equivocal.

The model, for the compaction of a uniform clay, can, therefore, be constructed assuming a progressive decrease in water content with depth. However, the presence of beds of coarser grain size can affect the rate of reduction of porosity, by acting as a duct to carry away the extruded pore water (Richards 1962). The return to normal porosity a few centimetres below the duct shows that the exclusion of this effect from the model is not critical. In fact, horizontal drainage becomes more important than vertical at greater depths, and experimental work has shown it is more effective by a factor of between 30% (Simons 1965) and 60% (Rowen 1959). Huisman (1964) has stressed the importance of the drainage of deltaic clays laterally into distributaries and distributary sands.

It has been suggested that anomalous fluid pressures can arise in thick sedimentary sequences (Oertel et al 1967, Bredehoeft et al 1968). At hydraulic conductivities above 10^{-6} cm/sec., only hydraulic pressures are encountered, but below 10^{-9} cm/sec. the pressures exerted by the liquid phase can equal or exceed the lithostatic pressure, causing compaction to cease. Conductivities in near surface clays are probably in the range of 10^{-6} to 10^{-7} cm/sec. (Terzaghi 1925, Zunker 1932, Carman 1939). Assuming this conductivity for the initial clay increment, the presence of anomalous fluid pressures, in the top 100 feet of a clay column undergoing compaction according to the model developed below, can be ascertained using the procedure outlined in appendix (10.3). The conductivity derived for the model, at a depth of 100 feet below the sediment surface, was 2.10^{-6} cm/sec., and compaction is unlikely to be interrupted by anomalous fluid pressures.

Given uniform clay content, mineralogy, organic content, sedimentation rate, etc., it appears that volume reduction is pressure controlled only to a fixed depth, and thereafter temperature is more important (Burst 1969). According to van Olphen (1963), normal crustal pressures are insufficient to expel adsorbed water from a clay, but the minimum limit is inversely proportional to the temperature. Although this effect cannot be ignored, it is unlikely that the transition from pressure to temperature dependence, at depths greater than 500 metres (Muller 1964) or pressures greater then 50 kg/cm^2 (Meade 1964), will be reached during the present simulation study.

From the above discussion, it appears that, for the present purposes, the compaction of clay can be considered in terms of overburden

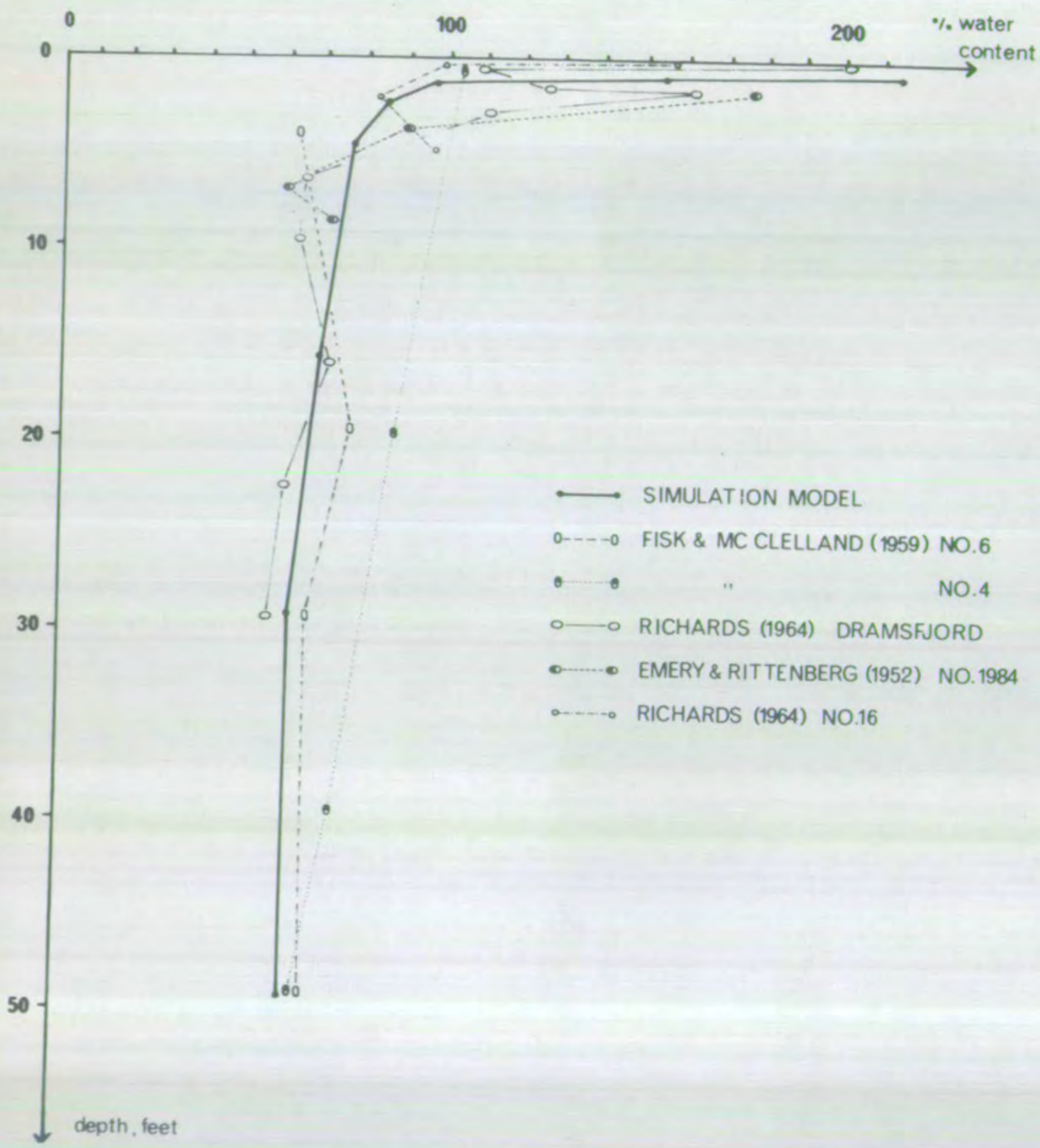


Figure(7.2.1) Simulation curves for the compaction of clay, silt and sand.

pressure. The downward force of each increment must, therefore, be computed, and to do this the bulk density must be known. Hedberg (1936) used the combined weight of the liquid and solid phases, arguing that the interstitial fluid cannot exert an upward force through buoyancy because it is held by adsorption. However, Terzaghi (1936) experimentally demonstrated that an upward force does exist where the void ratio is above 0.5. This work has been substantiated by Hubbert <u>et al</u> (1959) and can be interpreted in the light of the work of van Olphen (1963). Jones (1944) has suggested that when the void ratio falls below 0.1 the buoyancy effect disappears. In the simulation of Coal Measures sedimentation the void ratio is always above 0.5, so that an average specific gravity is used which allows for full hydrostatic uplift. Using this value, the downward pressure exerted by any increment can be computed as outlined in appendix (10.4). The derived equation for the increment pressure contains no void ratio term, under any guise, so that the pressure is constant regardless of the state of compaction. The total overburden pressure can be computed, therefore, as a constant ratio of the number of overlying increments.

Substitution of the model values into the derived equation gives the pressure due to any increment to be 0.008 kg/cm^2. In line with the policy of overestimating the effect of compaction this estimate was raised to 0.01 kg/cm^2, so that the pressure is slightly in excess of the true value for a clay with an initial water content of 200%.

The final stage, in the construction of the model of the compaction of clay, is to find an equation of void ratio against overburden pressure, which is consistent with the parameters defined and enumerated



Figure(7.2.2) Comparison of the simulation model of clay compaction with data from modern clayey sediments.

above and yet similar to experimental consolidation curves and observations from deep sediment cores. The simulation curve, shown in figure (7.2.1), is based upon the model parameters and Skempton's (1953) experimental curve for a clay with a liquid limit of 80%. Support for the use of the curve as a working hypothesis comes from its close similarity to data from modern clayey sediments, figure (7.2.2).

7.2(b) Compaction of silt

The model for the compaction of silt was taken directly from Skempton's (1953) figure 12, using the approximate relationship between void ratio and overburden pressure, for a sediment with a liquid limit of 30% dry weight. The void ratio of 1.2 disagrees only slightly with an experimentally determined void ratio of 1.23 (Einsele 1967), at a depth of about 30 cm. in pure quartz silt.

In the same way as for the model of the compaction of clay, the pressure exerted by each increment of silt was found to be 0.023 kg/cm^2. The relationship between void ratio and overburden pressure is shown in figure (7.2.1).

The ratio for the uncompaction of Westphalian siltstones, which have a void ratio of about 0.032 (Pritchard 1968, written communication), to their initial state, was obtained from the relationship shown in appendix (10.2), and found to be approximately 2:1. This ratio may be slightly high because of diagenetic changes of the type described in section (7.2(c)).

7.2(c) Compaction of sand

The Coal Measures sandstones have undergone extensive diagenetic changes, as described in section (8.11), including pressure solution and quartz precipitation. The volume change, therefore, should not be a simple function of the overburden pressure, but Maxwell (1964) found a linear decrease in porosity with depth in Pennsylvanian sandstones in the U.S.A. He attributed this relationship to the progressive increase in temperature with depth.

Using Maxwell's (1964) relationship, the porosity of 14% measured in the Parkgate Rock (Pritchard 1968, written communication) indicates an original porosity of 31%, and thus a void ratio of 0.31. This value is low, compared to 0.64 for a medium grained, well sorted sand (Taylor 1948), or 1.2 for a fine sand (Urul 1945). The average median grain size and quartile deviation of the Coal Measures sandstones, section (8.11), when plotted into Meade's (1968) figure 5, suggested an original void ratio of 0.7. Simple experiments, to determine the water content of crushed and saturated sandstones, gave a void ratio of 0.8. The experimental value is about 10% higher than that derived via Meade (1967), a factor which could be introduced by jarring and better packing (Athy 1930, Frazer 1935). A ratio of 0.7 was, therefore, taken as working hypothesis for the original state of the Coal Measures sandstones.

The initial void ratio of 0.7 and the value for the Parkgate Rock of 0.16 give a compaction ratio of 1.47. However, some of the reduction in porosity is caused by cementation and growth, and the actual ratio employed was reduced to 1.10. Although this decision may lead to a slight underestimation of differential compaction, the effectiveness of compaction in emplacing the sandstone bodies will be overstated.

The sand, in its initial state of best packing, does not compact under the influence of the range of pressures included in this simulation (Urul 1945). The downward pressure exerted by each increment was found to be 0.029 kg/cm^2, in appendix (10.4).

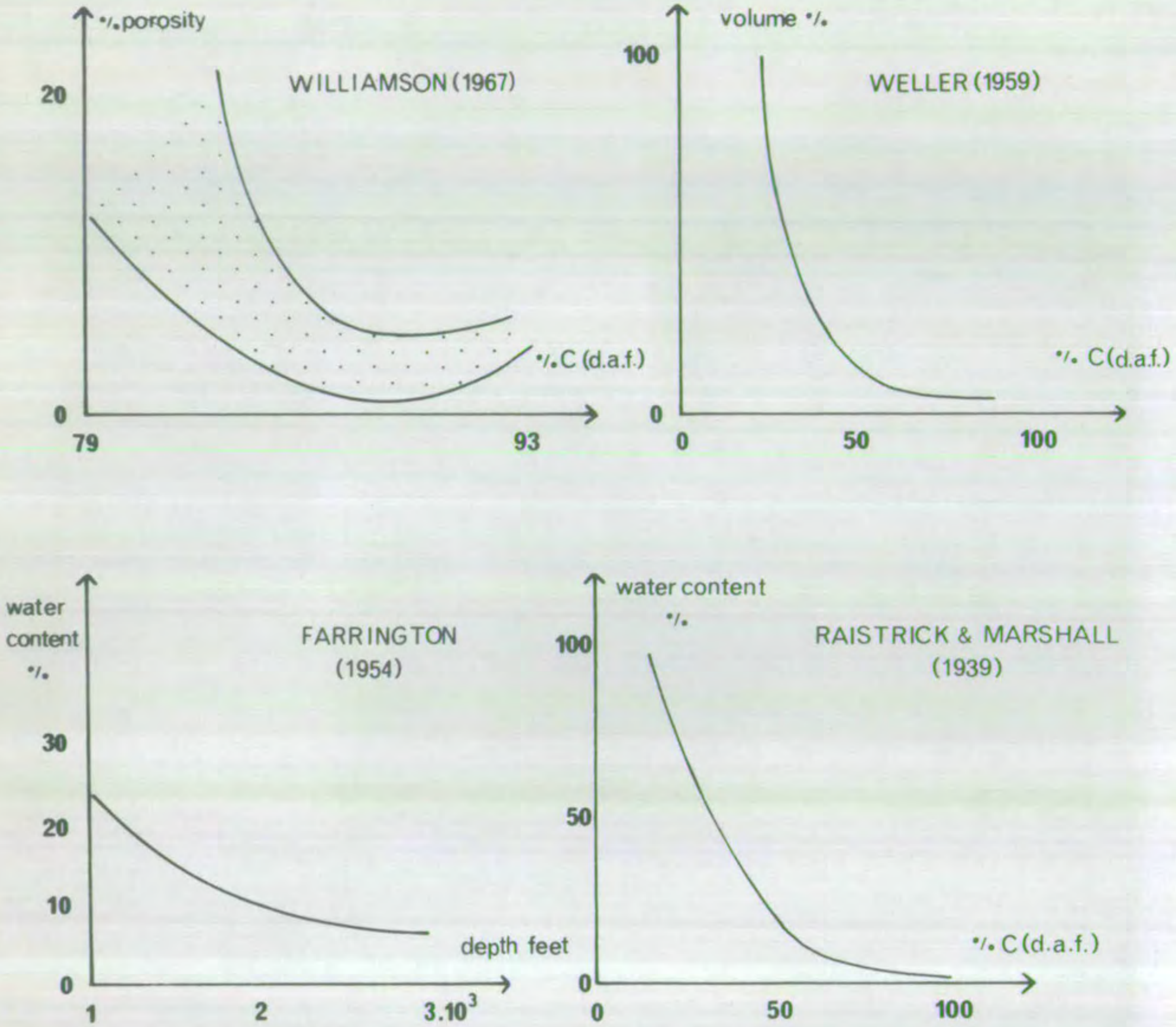
7.2(d) Compaction of peat

While the estimates of the compaction of sand, silt and clay have some foundation in fact, the model of the compaction of peat can only be considered as a reasoned guess. This is no cause for shunning the attempt, because only through criticism of crude models, such as this, can the truth be attained.

The model has been built upon information from modern peats and ancient coals and lignites, and forms a bridge between the two. However, the physical nature of the Carboniferous peat is not, and probably never will be, known.

The compaction of peat is not a simple function of the overburden pressure, but the apparently progressive volume reduction with depth of burial suggests that the pressure may be used as a proxy variable for a whole gamut of controls. Wood tissue is decomposed by the action of micro-organisms, in the initial oxidising stage by fungi and bacteria and in the later reducing stage by actinomycetae and anaerobic bacteria (Teichmuller et al 1967). Microbial activity decreases with depth of burial.

Drying of peat, caused by a drop of the water table, causes an



Figure(7.2.3) Information relating to the conversion of peat to lignite to coal.

irreversible volume reduction (Fosberg 1966). This imponderable factor has not yet been included in the model and will thus introduce a certain amount of error, even though Huisman (1966) has shown that in tropical deltas the water table is usually everywhere close to the surface.

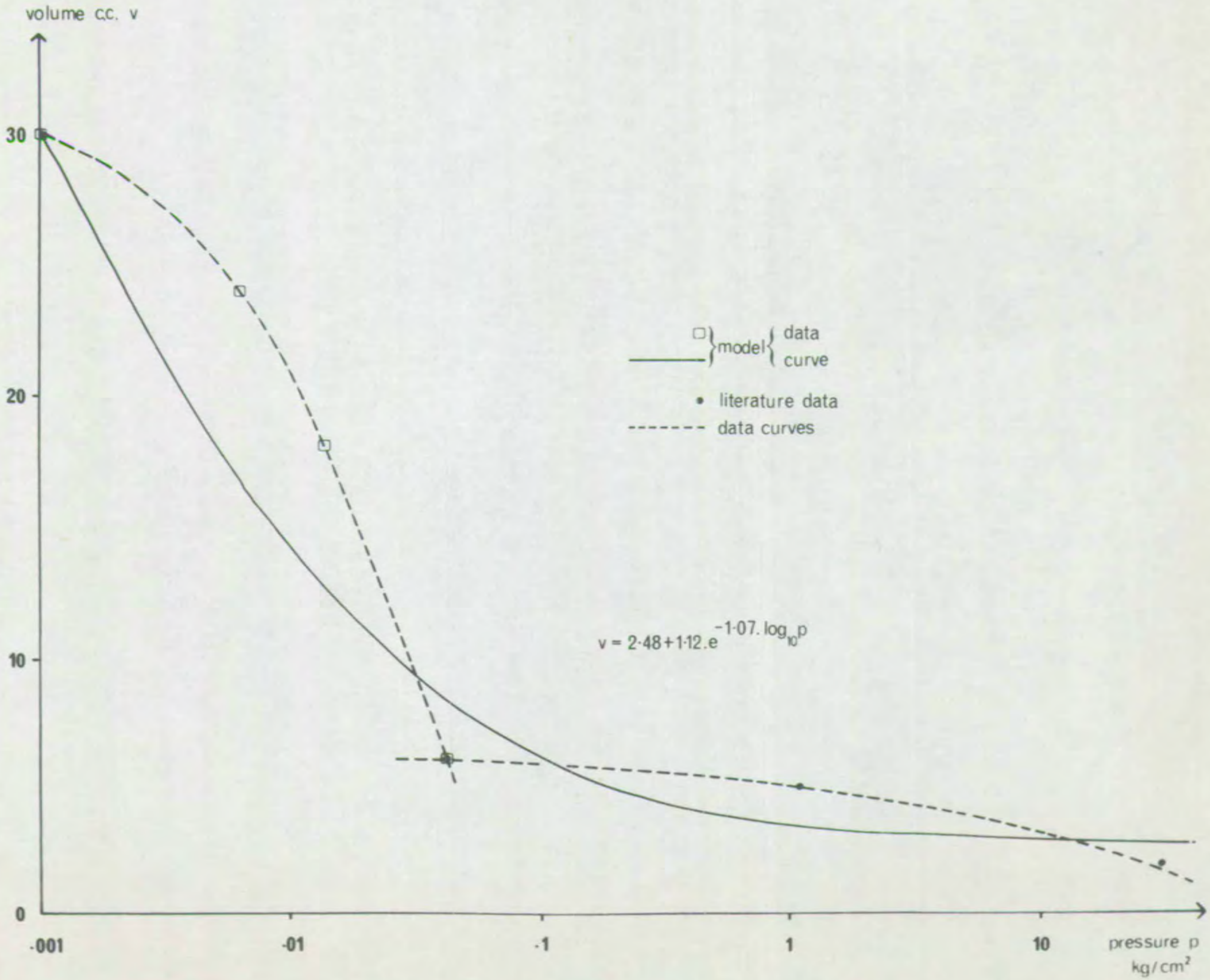
The variability of the early stages, probably magnified by differences in plant material, nutrient supply and many other factors, apparently gives way to a more ordered process at greater depths of burial (see Trotter 1950). The fairly simple curves of water content, porosity and volume against per-cent carbon (d.a.f.), given by Raistrick et al (1939), Williamson (1967) and Weller (1959) respectively, and water content against depth (Farrington 1954), are shown in figure (7.2.3).

The model of the compaction of peat must, therefore, be considered in two stages. First, woody material is converted to peat with a loss of the structural framework, and air and gases produced by decomposition are expelled. Some solid material goes into solution and is lost. Second, the system can be considered to consist of solid and liquid phases only, and volume reduction is simply related to depth.

In a peat bog, about 30 feet thick, there is a 5:1 volume reduction between the top and base, or between the Top and Pot peat (Trotter 1950, Williamson 1967). Pot peat has many characteristics in common with lignite (data from Teichmuller et al 1967, Trotter 1950) and probably marks the beginning of the second compactive stage. The average water content of modern Top peat ranges between about 90% and 98% wet weight Teichmuller et al 1967) and the transition stage occurs at a water content of about 75% (Kayser 1952). However, tropical peats tend to have lower water contents than the average (van der Molen et al 1962) and more realistic estimates are 90% and 70% respectively. The density of Carboniferous wood will never be known, and Williamson's (1967) estimate of 1.5 has been used. This figure is probably slightly high but since the effect of the error will be to overestimate the effect of compaction, it was accepted.

Using these figures, a model for the compaction of peat, to an equilibrium thickness of 30 feet, can be constructed, as outlined in appendix (10.5). The use of linear interpolation, for the iteration involved in the computation, is not strictly justifiable but necessary. The results show that a 30 feet thick peat bog is composed of 60 increments and, therefore, equivalent to 60 feet of totally uncompacted peat. The 60th increment has a volume of 6.1 c.c. and sustains an overburden pressure of 0.041 kg/cm^2. This point can be plotted into Raistrick and Marshall's (1939) curve, figure (7.2.3), using the known water content of 70% wet weight. Farrington (1954), figure (7.2.3), found that the water content at a depth of burial of 1000 feet was 22% wet weight. This figure is equivalent to a water content of 31% dry weight and void ratio of 0.47. Using the supposedly constant volume of the solid phase (1.38 cc.), the increment volume must be 2.03 cc. If the overburden is clay, 1000 feet at compactional equilibrium is composed of approximately 1880 increments and, therefore, exerts a pressure of approximately 24 kg/cm^2. Intercalations of sand and silt would increase the computed pressure towards an estimate of 35 kg/cm^2, derived from Weller (1959). A compromise of 30 kg/cm^2 was employed in subsequent calculations.

Although the first stage of the model was computed for the compaction of peat under its own weight, the results apply equally to the



Figure(7.2.4) A model for the reduction in volume, related to increasing pressure, during the transition from peat to lignite to coal.

increment volume reduction under any overburden. The compaction curves derived from the model parameters and the literature data of figure (7.2.3) may, therefore, be linked together, and a single curve used to approximate the volume reduction with increasing overburden pressure, figure (7.2.4). This continuous curve becomes invalid above 10 kg/cm^2 where the error is rapidly magnified.

To complete the model, it is necessary to produce an estimate of the compaction ratio between the coals in the East Midlands Coalfields, and the initial increment of Top peat. Raistrick and Marshall (1939) suggested that a ratio of 15:1 is not excessive, although they were probably referring to the thickness of the peat bog.

Coal rank maps of the East Midlands Coalfields (Wandless 1960) show a range in per-cent carbon (d.a.f.) between 78% and 88%, which embraces an average of 81% given by Jolly et al (1968). Plotting the 81% average into Weller's (1959) curve of volume against per-cent fixed carbon, figure (7.2.3), suggests a volume of 5% of the original, and thus a compaction ratio of 20:1.

7.2(e) Data from the East Midlands Coalfield

Of the 306 available records, 73 were selected for use in the regeneration of Coal Measures sedimentation. Most recent boreholes have been sited in the East of the study area, so that, during compilation of the data set, a balance had to be struck between information quality and distribution. Eventually a set was obtained which was very well distributed over the coalfield and yet consisted of a uniform and fairly high standard of information. For detailed studies, in restricted areas, material of the highest quality could be employed. It was deemed essential to have detailed sections of all coals over a few inches in thickness. Additional information, of this kind, was obtained from Eden et al (1957), Edwards (1951, 1967) and Smith et al (1967), but the bulk of the data was obtained with the kind permission of the National Coal Board, East Midlands Division.

7.3 Experiments with the Compaction Model

The model, which has been developed, can now be used not only to measure the effects of compaction in the Coal Measures rocks, but also to test some currently held hypotheses about the role played by compaction in the development of sedimentary sequences.

The compactional state of the sediments at the time of deposition is critical. In general, if the sedimentation rate is slow time is available to reach compactional equilibrium and the individual increments can sustain the overburden pressure, without the assistance of anomalous fluid pressures. If the sedimentation rate is high, the restricted permeability prevents the rate of adjustment of the water content matching the rate of increasing overburden pressure. If a pile of sediment is in a state of compactional disequilibrium it will react to a greater extent to the compactive stress of later sediments than if it had been accumulated at equilibrium, under conditions of slow sedimentation. It is possible, therefore, that the similarities and differences between interval thicknesses, found in section (6), could arise through compaction of sediments at disequilibrium, thereby invalidating the use of the compaction model. It is possible to assess the amount of disequilibrium from the consolidation rate, for the clay compaction model, and from the effect of compaction of the substrate on the development of peat.

7.3(a) Consolidation rate

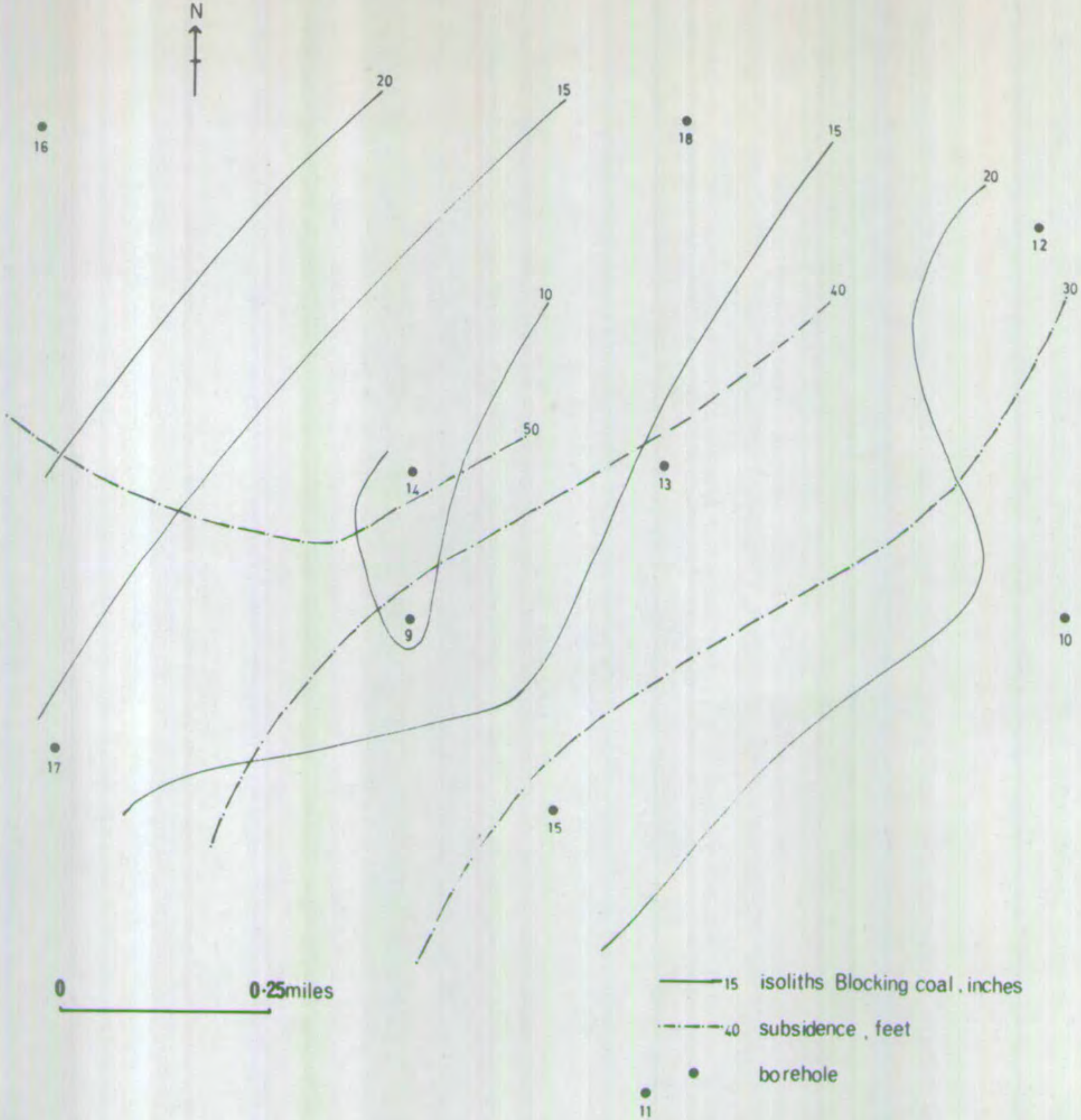
Equations 10.6(a) and 10.6(b), appendix (10.6), can be used to compute the time required for any number of increments of clay to reach any state of compaction, up to and including equilibrium. Results for 50% and 100% of equilibrium are listed in table (7.3.1), and may be interpreted in terms of the sediment accumulation rate. For example, if 100 increments of clay were deposited quickly enough so as to form a sediment pile 100 feet thick, reduction to equilibrium thickness (39.6 feet) would require 36,800 years, but only 1500 years would be needed to reach 50% of the equilibrium state (79.8 feet). If, with a more moderate accumulation rate, the sediment pile was already at 50% of the equilibrium state at the end of the period of deposition, the time required for consolidation to equilibrium would be reduced to 35,300 years.

These figures should be treated with caution bearing in mind Taylor's (1948) statement that "settlement analyses usually give results which at best are crude estimates".

Table(7.3.1) Consolidation rates to two states of compaction for the clay simulation model ; for the theory see appendix(10.6).

		u = 50%		u = 100%		
h	h^2	t	T	t	T	d
2	4	1.95	0.6	1.9	14.7	14.1
5	25	4.4	3.8	3.8	92.0	88.2
10	100	8.2	15.0	6.4	368.0	353.0
15	225	11.8	33.8	8.6	828.0	794.0
20	400	15.4	60.0	10.8	1472.0	1412.0
25	625	18.8	94.0	12.8	2300.0	2206.0
30	900	22.4	135.0	14.7	3312.0	3127.0
40	1600	29.3	240.0	18.5	5888.0	5648.0
50	2500	36.1	375.0	22.2	9200.0	8825.0
70	4900	49.7	735.0	29.3	18032.0	17297.0
100	10000	79.8	1500.0	39.6	36800.0	35300.0
286	81796	193.0	12269.0	100.0	301009.0	288740.0

h = number of increments ; u = compactive state of sediments as a % of equilibrium ; t = thickness in feet at u% ; T = time in years to reach u% of equilibrium ; d = time in years needed to pass from 50% to 100% of equilibrium.



Figure(7.3.2) Information from Parkmill Colliery, Yorkshire.

7.3(b) Peat thickness and substrate compaction

The relationship between peat and substrate can be demonstrated in the case of thick sandstone belts in the Coal Measures (section 8), and can be shown to be a function of positive topographic expression and compaction (see also Trueman 1954 fig.1.6). Peat thickness can also be shown to be related to subsidence on the scale of the Pennine Basin (section 7.4). If the effects of downwarping and topographic expression could be removed, the thickness of peat could be used to compute the amount of compaction, occurring in the substrate, during its formation.

Data were available which met these requirements. The information consisted of 10 underground boreholes in the Parkmill Colliery in Yorkshire, which were distributed over an area less than one mile square, figure (7.3.2). Operator variance can be ignored, since all the sections were described by one geologist (R.F.Goosens), who also provided details of the constitution of the rock terms employed. The information referred to a section of strata between the Wheatley Lime and Whinmoor coals (Communis Zone). One particular coal, the Blocking, was selected for analysis because it was present in the most records (8) and showed an appreciable range in thickness, from 9 to 28 inches (23 to 71 cm.). Correlation, by means of the widespread Low Estheria Band, shows that the Blocking coal is equivalent to the upper part of the Silkstone group of coal seams, which immediately underlies the Threequarters coal.

The study area is so small that it is probable that all subsidence controls, recognised in the East Midlands area, can be considered regional. The regular, belt-like pattern of Blocking coal isoliths suggests that the principal control is local but not residual. A number of different hypotheses of the controls of coal thickness can be statistically tested.

To test the hypothesis that coal thickness is controlled by subsidence on the local scale, the induced compaction in the sediments between the Top and Bottom Estheria coals, convenient names for two thin coals above and below the Estheria Band, was computed from the reduction from equilibrium thickness, under the influence of the overburden stress exerted by the sediments between the Top Estheria coal and the base of the Blocking coal. The amount of induced compaction was subtracted from the equilibrium thickness of the sediments, between the Top Estheria and Blocking coals, to give the necessary subsidence. The data are shown in table (7.3.3). The correlation coefficient (-0.27), computed for equilibrium peat thickness and subsidence, indicates that the hypothesis of zero correlation cannot be rejected at the 5% level, and that, therefore, peat thickness is not related to, nor controlled by, subsidence. However, it should be noted that the population coefficient, based on this small sample, could range between -0.80 and +0.50, so that the conclusion is open to sampling error. On the other hand, the lines of equal subsidence in figure (7.3.2) have a strong Pennine Basin trend, which contrasts markedly with the local nature of the coal isoliths.

A second hypothesis, that the peat thickness is controlled by the induced compaction, where its expression lags behind loading, can be tested by using the data of table (7.3.3). The correlation coefficient (-0.19) indicates that the hypothesis of zero correlation cannot be rejected at the 5% level, although again the population coefficient can

a	b	c	d	e	f	g
14	9	10.0	51.1	9.4	27.4	42.0
9	10	10.8	39.2	11.3	22.6	41.1
17	14	13.2	47.0	11.7	20.8	40.2
13	16	14.1	38.2	10.4	27.3	47.0
10	21	16.7	24.2	11.0	34.1	52.6
11	21	16.7	18.6	11.9	34.6	45.1
12	22	17.3	31.5	13.1	33.9	54.8
16	28	19.8	52.8	6.5	37.8	57.6

Table(7.3.3)

a Parkmill Colliery, underground borehole number

b Blocking coal thickness in inches

c Blocking coal, equilibrium peat thickness in feet

d Subsidence necessary to emplace the sediments between the Blocking and 'Top Estheria' coals, in feet

e Induced compaction in sediments between the Blocking and Top Estheria coals.

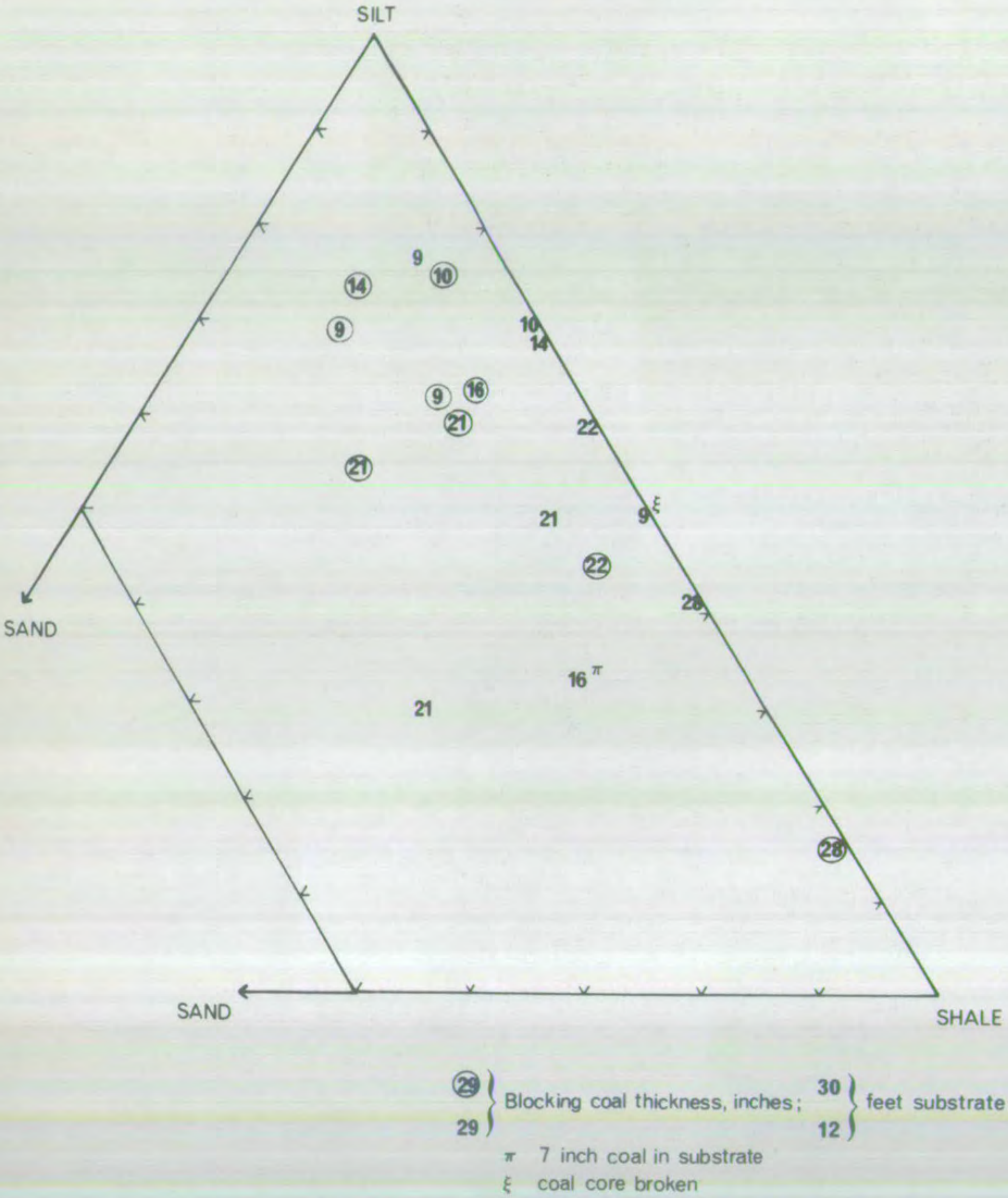
f Potential compaction in 70 increments of substrate beneath Blocking coal.

g Potential compaction in 100 increments of substrate beneath Blocking coal.

have a wide range of values (-0.76 to +0.55), and the previous remarks, on sampling, apply equally. Peat thickness is, therefore, not controlled by relict induced compaction.

A third hypothesis is that the peat thickness is controlled by the delayed adjustment to equilibrium of the immediate substrate, disequilibrium having arisen from a high sediment accumulation rate. This hypothesis can be tested by comparing the equilibrium Blocking peat thickness with the potential compaction in the substrate, which can be computed as the difference between the number of increments, in feet, and the equilibrium thickness. Provided that the inception of peat formation began at the same time, throughout the square mile under consideration, and the permeability conditions are about the same in each locality, the relative remaining compaction will always be proportional to the relative potential compaction, whatever the compactive state of the substrate at the beginning of peat growth.

How much of the substrate should be taken into consideration for computation of the potential compaction? Too few increments will produce too little compaction to emplace the peat, but too many will include sediment which could be in a highly compacted state at the inception of peat growth, and serve only to mask the influence of the overlying sediments. If peat thickness and potential compaction are functionally related then, theoretically, their mutual regression line must pass through the measurement origin, where the correct number of increments has been employed, because the relative remaining compaction must be zero where the potential is zero. The effect of more deeply buried sediment,



Figure(7.3.4) Blocking coal thickness plotted into a textural triangle (end members: clay, silt, sand) for 12 and 30 feet of substrate.

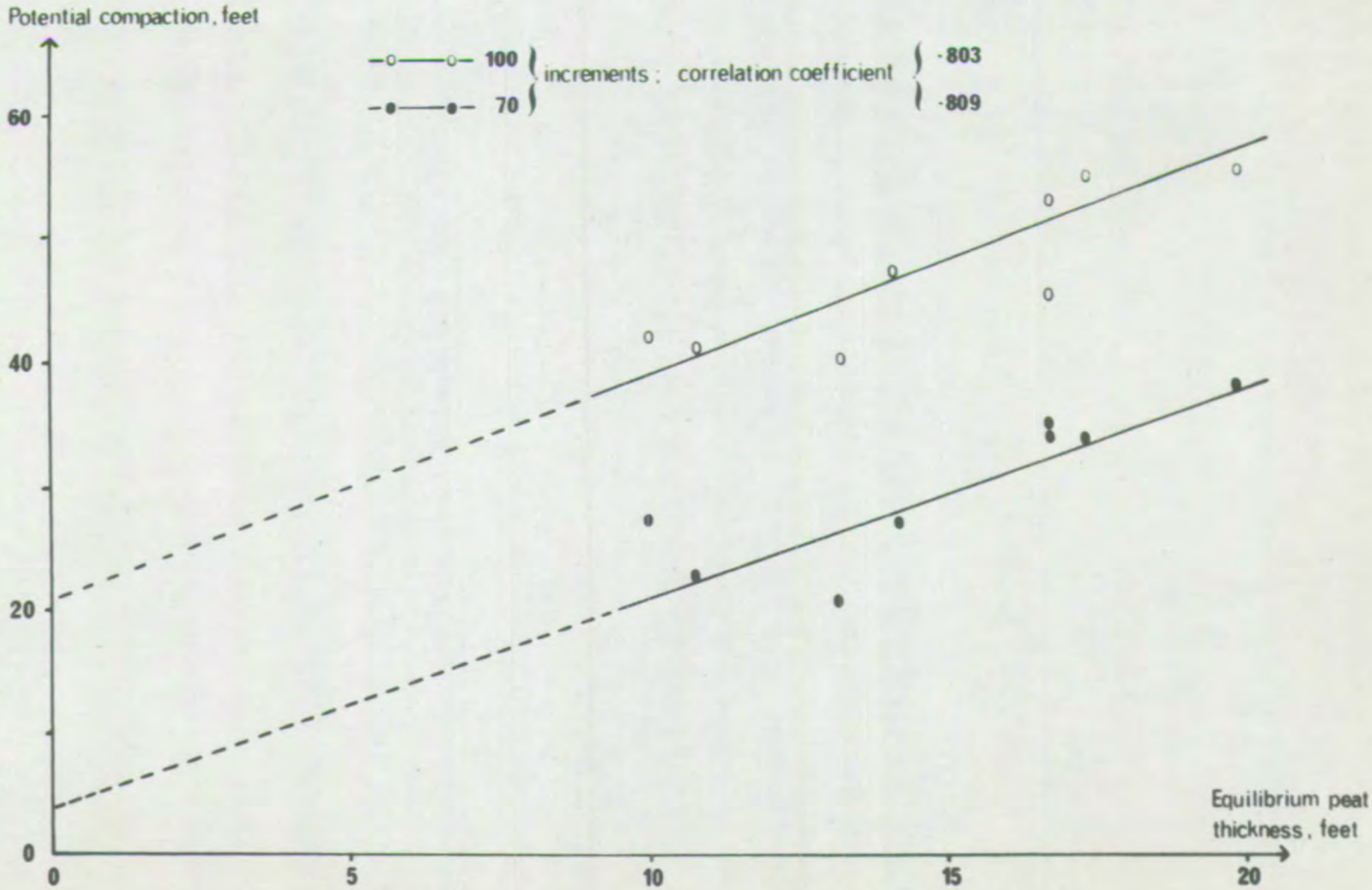
which will have gone further towards the equilibrium state, will be to add potential which can never be realised.

As a first approximation, Blocking coal thickness, in inches, was plotted into a per-cent sandstone, siltstone and shale triangle, at points computed for depths to 12 and 30 feet in the substrate, figure (7.3.4). The much better ordering of the 12 feet data set with respect to the per-cent shale end-member suggests that about 70 increments should be used in the analysis.

Figure (7.3.5) shows the relationship between the equilibrium thickness of the Blocking peat and the potential compaction in 70 increments of immediate substrate. The correlation coefficient (+0.81) is significant at the 5% level, and demonstrates that a functional relationship may well exist. The population coefficient could lie between +0.2 and +0.94. A similar result for a comparative data set of 100 increments (+0.80) bears out this conclusion.

The reduced major axes, of the 70 and 100 increment data sets, are almost parallel, and the constant displacement probably arises from the influence of unrealised potential. The reduced major axis of the 70 increment data does not quite pass through the origin. However, this set was used subsequently, to save recomputation of the precise line, which would refer to a number of increments between 65 and 70.

The gradient of the reduced major axis which passes through the origin is 1.7, or approximately 2. Therefore, the equilibrium thickness of peat is equivalent to half of the potential compaction. Reference to table (7.3.6) shows that development of the peat must occur during the last 50% of compaction of the substrate to equilibrium. If, for example,



Figure(7.3.5) Relationship between equilibrium thickness of Blocking peat and the potential compaction in 70 and 100 increments of substrate.

U % of equilibrium state of compaction	time in years to reach U % state	sedimentation rate (cm./year) to restrict compaction to U % of the equilibrium state.
10 %	36.3	58.4
20 %	107.2	19.8
30 %	254.8	8.4
40 %	470.0	4.6
50 %	735.0	2.9

Table(7.3.6) Time required to reach U % of the equilibrium state and the sedimentation rate necessary if the sediments are to be restricted to the U % state of equilibrium. All values refer to 70 increments of clay undergoing compaction according to the simulation model.

peat growth commenced on a substrate at 10% of the equilibrium state, and ceased at 60%, the sediments would have had to be accumulated at the rate of 58.4 cm/year. Compare this rate with the Mississippi Delta where 500 feet sediment has accumulated in 40,000 years (Fisk 1960), suggesting an accumulation rate of 0.38 cm/year if the sediment is all sand, or 1.0 cm/year if it is all clay. To get a reasonable figure for the accumulation rate, of the sediments below the Blocking coal, it is necessary to postulate that peat growth began when the substrate was compacted to 50% of equilibrium.

Two important conclusions can be drawn from these results. First, the Blocking peat took some 17,300 years to accumulate (see table 7.3.1) compared to 735 years for the underlying 70 increments of sediment. Therefore, it is probably better to employ a conceptual model, of the Westphalian Pennine Basin, in which peat-swamp conditions are infrequently interrupted by periods of clastic sedimentation, rather than a model where peat growth and clastic sedimentation are concomitant. Second, at the time of completion of the development of the Blocking peat, the substrate must have been almost at compactional equilibrium. Taking into account the long time for construction the Blocking peat was probably also at equilibrium. No lag effects arising from disequilibrium can, therefore, influence the sediments above the Blocking coal.

Expanding the second conclusion into the general context of this thesis, the negative correlations arising between intervals separated by coals can only be due to the compaction, from the state of equilibrium, induced in the lower interval by its successor. The compaction model, which computes equilibrium thicknesses, may, therefore, be applied directly in most cases.

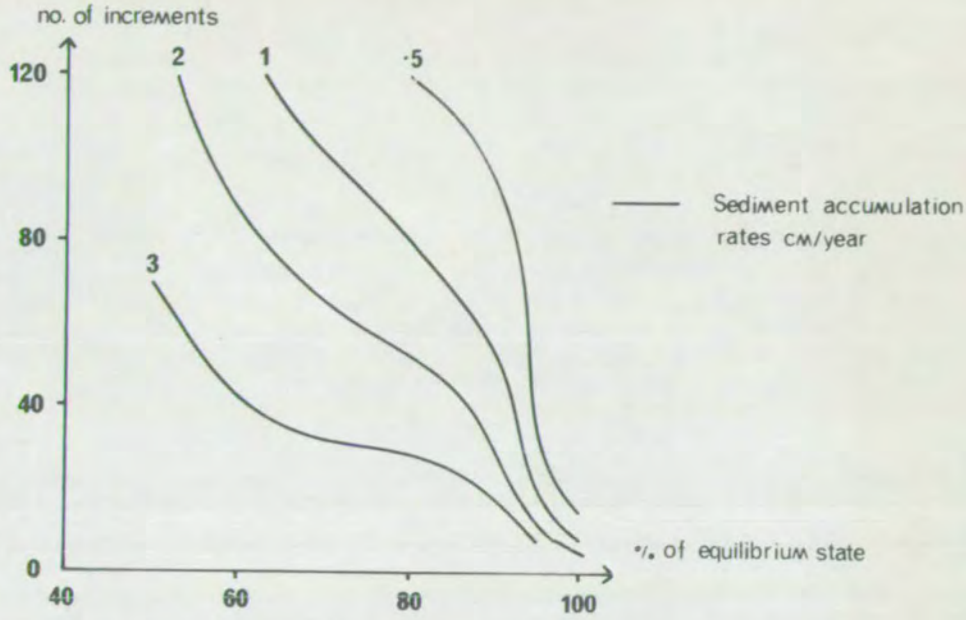
7.3(c) Induced compaction (clay)

Space is created for sediments by the compaction they induce in the substrate. To test the suggestion, of section (6), that, on the local scale, sediment thickness is controlled by differential compaction, it is now possible to measure the induced compaction in any substrate by any overburden.

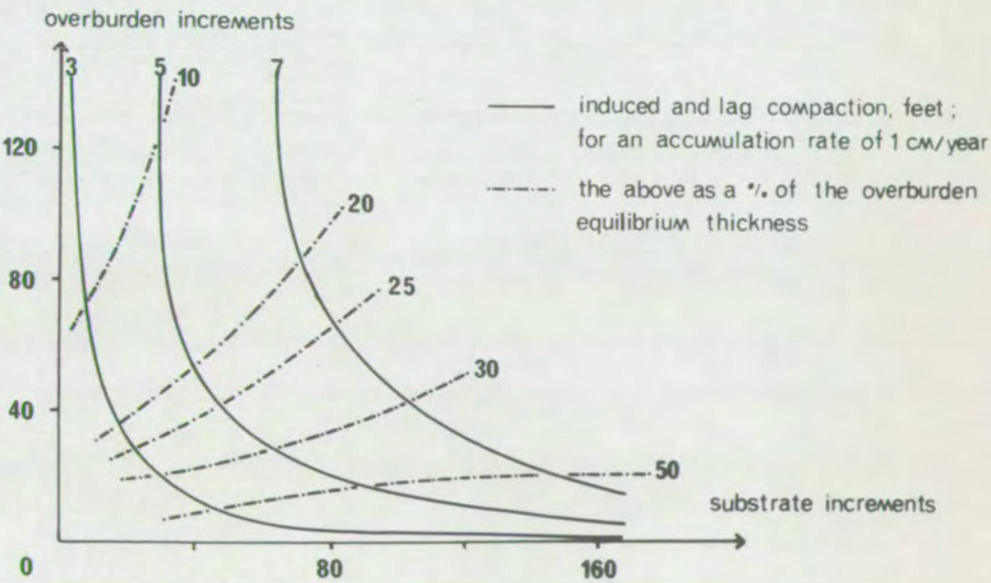
Ignoring, for the moment, the special case of sediments separated by a layer of peat, the disequilibrium in the substrate may be estimated, from figure (7.3.7), for any sediment accumulation rate. The induced compaction plus lag compaction, arising from disequilibrium for accumulation at 1 cm/year, have been computed over a range of thicknesses of substrate and overburden. The sum of the results, the total induced compaction, is shown in figure (7.3.8). Except for the smallest thickness of overburden on the largest of substrate, it can be seen in figure (7.3.8) that it is impossible to induce enough compaction to create space for the new sediment.

Referring to the results of section (6), the difference between maximum and minimum thickness of the intervals, which have negative correlations with their neighbours, is greatly in excess of the small thicknesses of overburden which can be emplaced by compaction. The differences in thickness, computed in an equilibrium compaction state, must be used in preference to absolute values, because of the possible effect of basinal downwarping or eustatic rise in 'sea' level.

The ratio of induced compaction to overburden would be even smaller if a slower sedimentation rate had been assumed for the substrate,



Figure(7.3.7) Equilibrium states for thicknesses of sediment (clay), up to 120 increments,accumulated at various rates.



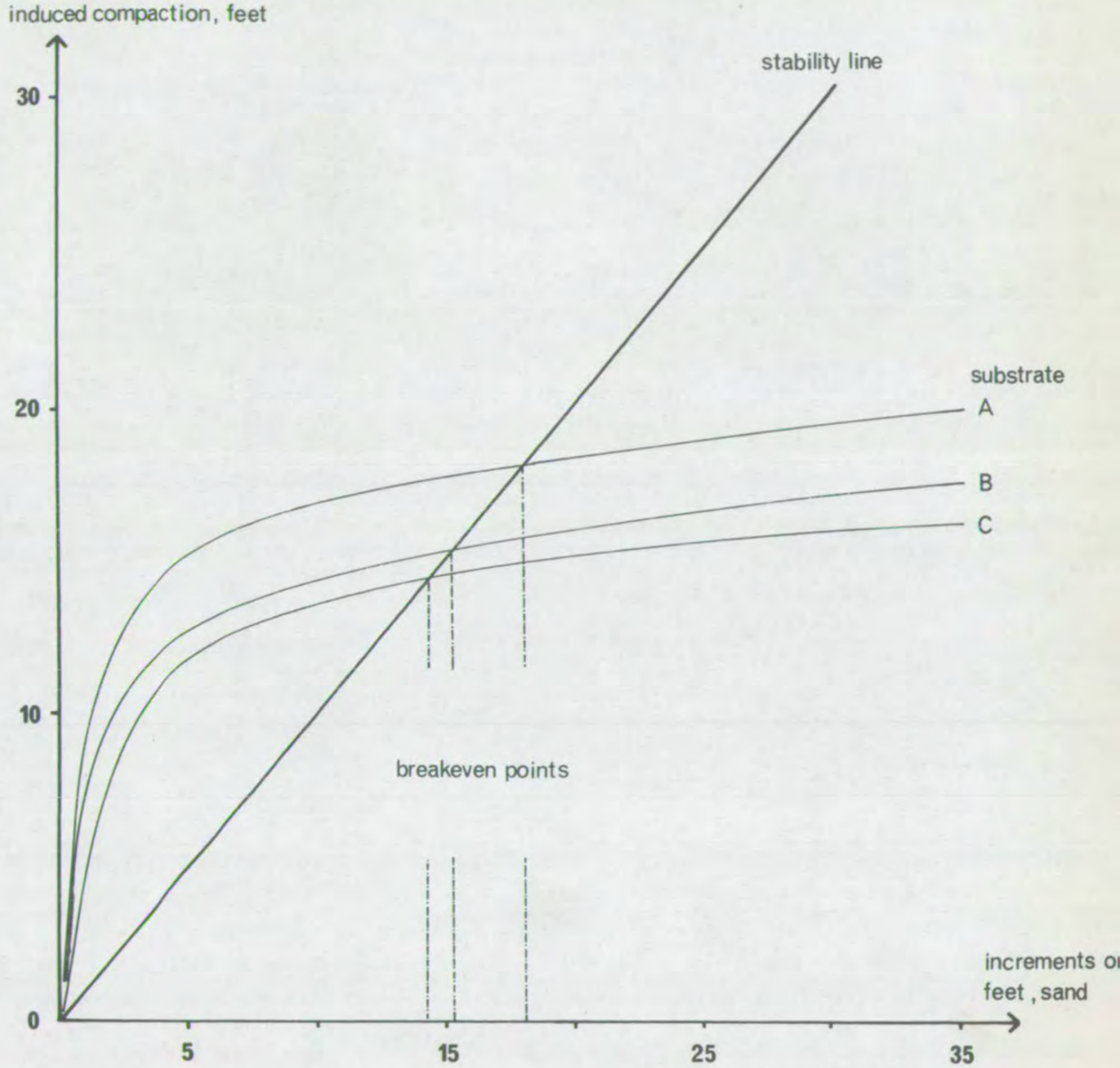
Figure(7.3.8) The compaction induced in an unstable substrate by an unstable overburden; substrate and overburden both accumulated at 1 cm./year.

or if the overburden was considered to be in a disequilibrium state, which is likely, or the substrate at equilibrium. The ratio could have been made slightly higher if a faster, more unrealistic, accumulation rate had been employed.

7.3(d) Induced compaction (peat)

In the special case of sediments separated by a layer of peat, the clay substrate will be at compactional equilibrium and the induced compaction must be less than that given in figure (7.3.8). This reduction is compensated by the large amount of compaction which can be induced in a thickness of peat. Initially, the addition of an increment of sand, silt or clay induces more compaction, in a peat substrate, than the space it occupies. Therefore, the level of the sediment surface drops even though accumulation is proceeding.

This phenomenon is illustrated in figure (7.3.9), which shows the induced compaction in substrates of different peat and clay mixtures, at equilibrium, caused by the addition of sand. The breakeven point, where the overburden no longer creates more space than it occupies, is dependent upon the thickness of peat and only slightly influenced by the thickness of clay. The importance of this reaction is to localise the early stages of deposition. For example, 20 feet of sand could be deposited by a stream without a change in base level. The same would be true for about 10 feet of clay. In the Coal Measures rocks, therefore, the influence of overcompaction must be taken into account for the basal

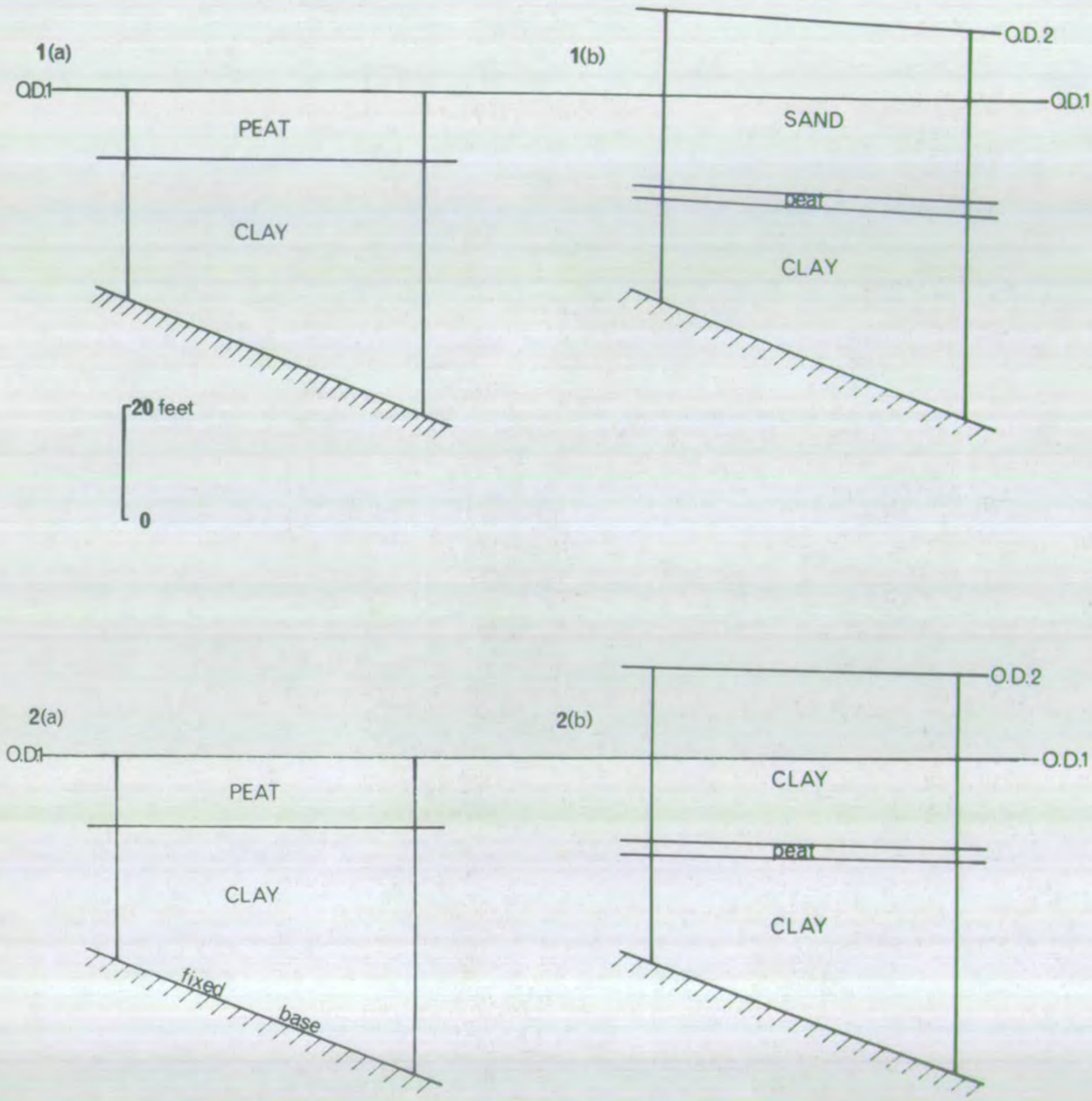


Figure(7.3.9) Experiments to demonstrate the possible early stage overcompaction of peat.

Substrate A - peat 40 feet over clay 40 feet

B - peat 20 feet over clay 60 feet

C - peat 20 feet over clay 40 feet



Figure(7.3.10) Experiments to demonstrate that topographic irregularities can hardly be passed on via compaction. The necessary subsidence is given by O.D.2 - O.D.1

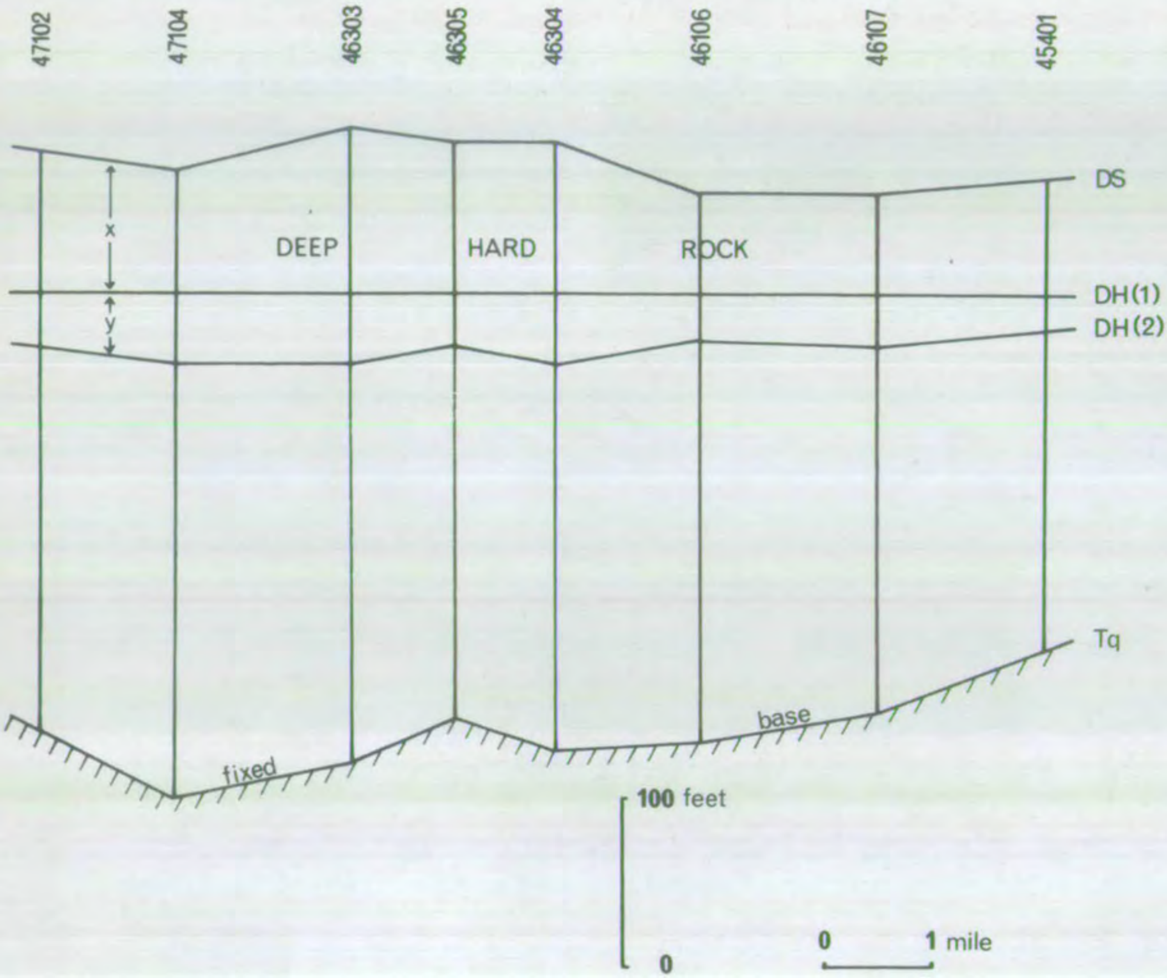
18 feet of a sandstone over-lying a 2 feet thick coal, but only the basal 3 feet of shale.

7.3(e) Inheritance of topographic irregularities

The concept of the inheritance of topographic irregularities through compaction has been put forward (Edmunds 1968) to explain the superimposition of thick wedges of sediment. As shown in figure (7.3.8), the amount of induced compaction is small, so that even if this process is operative its effect will be very slight. A uniform layer of sand was added to a wedge, of clay and peat, filling a topographic irregularity in fixed base, as part of the simulation experiment illustrated in figure (7.3.10). In a second run, a uniform layer of clay was substituted for the sand. The results show that while the new sediment surface has a slope imitating the fixed base, the topographic expression is reduced from 19.4 feet to 2.5 feet and 1.0 feet for the sand and clay layers respectively. Reduction of the topographic expression by the same factors, following later sedimentation, would successfully reduce the irregularity to total insignificance.

7.3(f) Emplacement of sandstones

In the equilibrium state, the sandstone belts of the Coal Measures are much thicker than the laterally equivalent shales (section 8.3, figures 8.3.4 to 8.3.14). Unless the sandstones had positive topographic expression at the time of deposition, they must have been emplaced

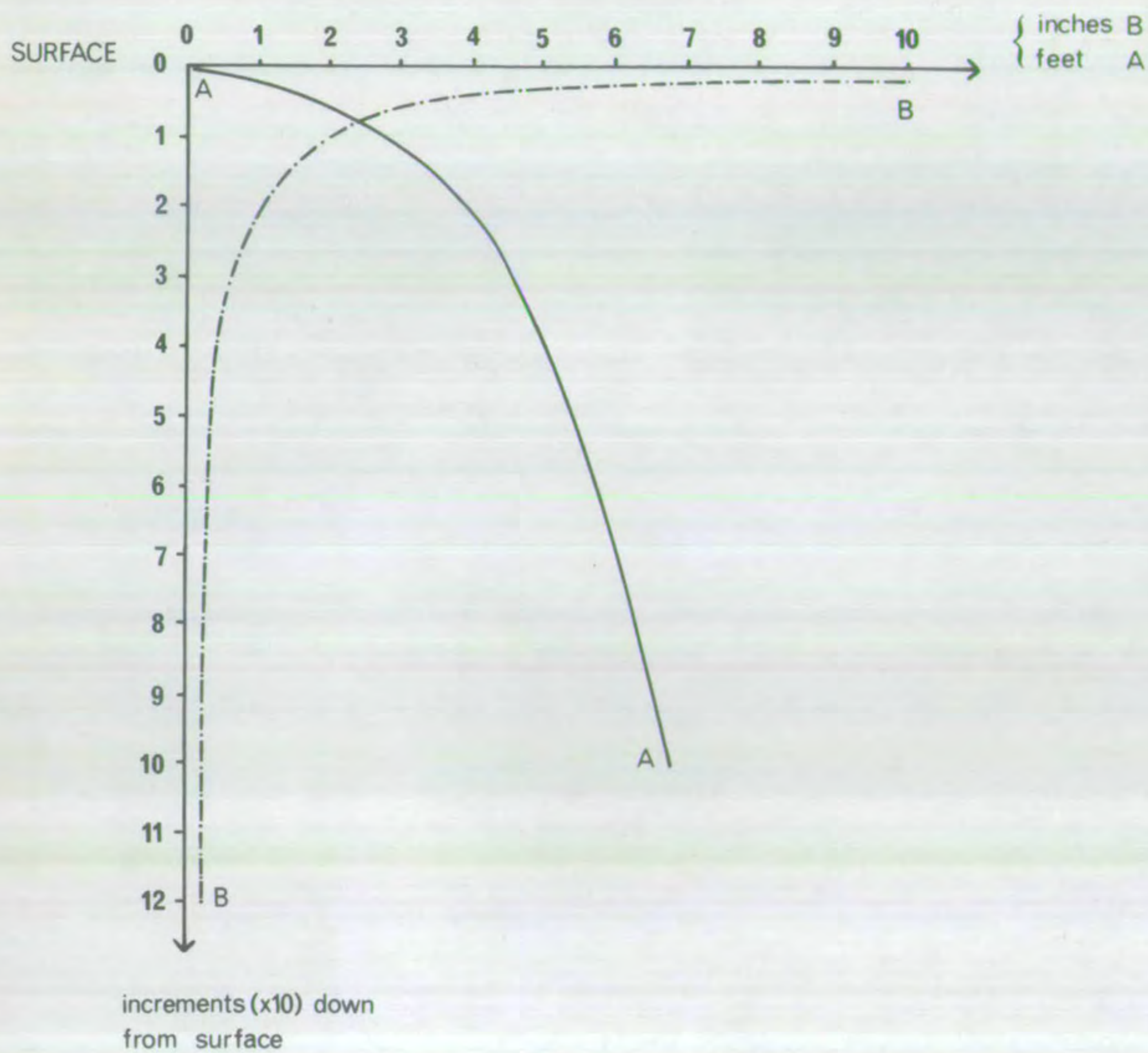


Figure(7.3.11) To show the role of subsidence in the emplacement of sandstones.
DH(1) and DH(2) - original and final positions of the Deep Hard coal
y - induced compaction
x - necessary subsidence if the Deep Soft coal is to be formed at 'sea level'.

by some mechanism. Since the sandstones correspond to many of the local thickness irregularities described in section (4), the negative correlations between local components (section 6) suggest emplacement through compaction. However, computation of the induced compaction in the sediments between the Deep Hard and Threequarters coals shows that the space created is totally insufficient to emplace the Deep Hard Rock, figure (7.3.11). It is, therefore, necessary to conclude that this sandstone body was emplaced by local subsidence.

7.4 Compaction and Subsidence in the Coal Measures

The 73 boreholes, selected for accuracy and position, were totally uncompacted and recompacted to equilibrium using the model developed in section (7.2). At each datum horizon, that separates the intervals of Coal Measures sediments, the model was stopped and the equilibrium thicknesses and induced compaction computed. The necessary subsidence was computed as the difference between the thickness and the induced compaction. Lag compaction, arising out of disequilibrium, was ignored because the intervals are separated by peat (section (7.3 b). In order to compensate for the control of peat thickness by lag compaction, the necessary subsidence was computed less the thickness of the surface peat in the case of individual intervals, or less the sum of surface peat thicknesses for total subsidence. The induced compaction was taken to include the contribution from buried peat.



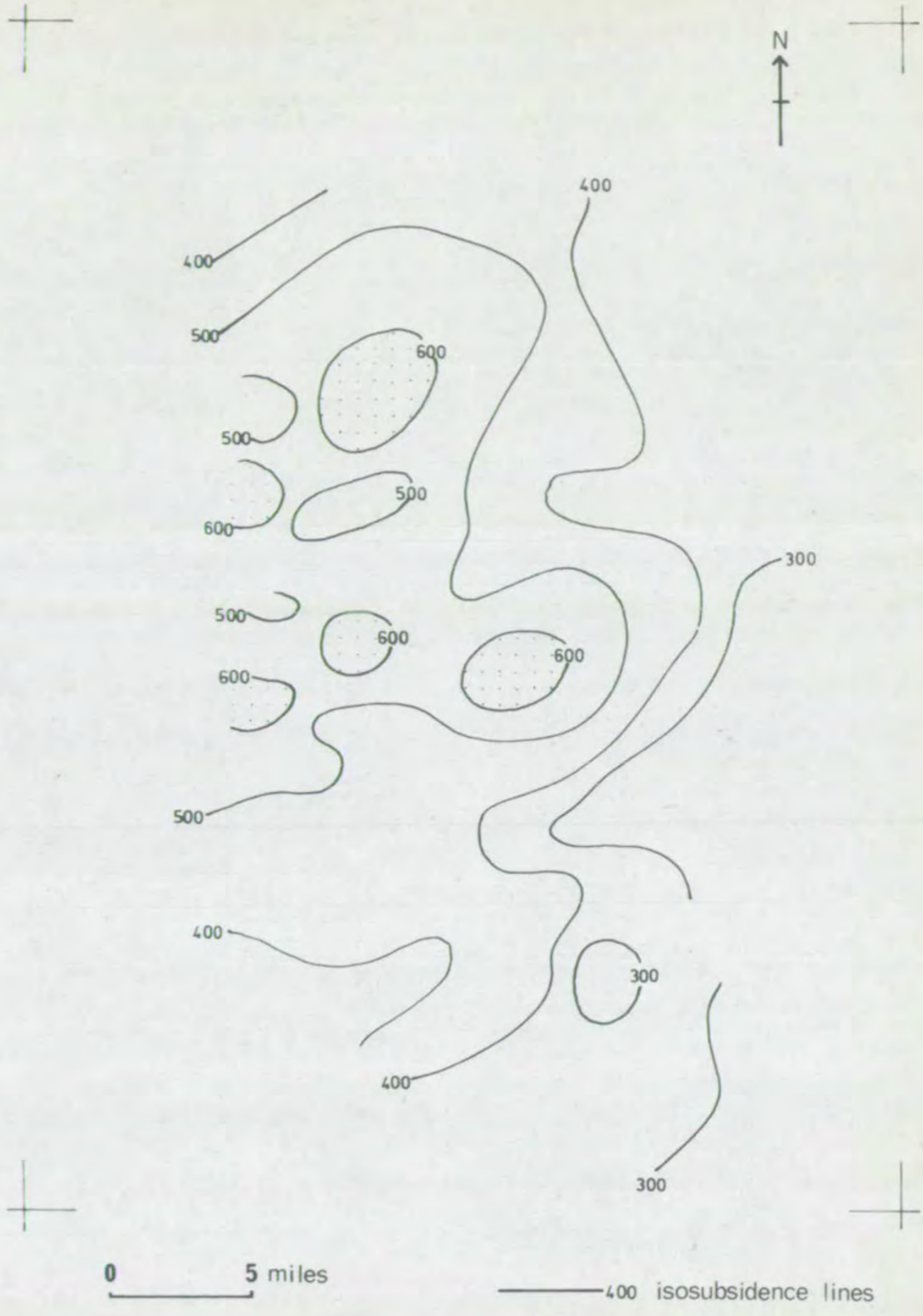
Figure(7.4.1) Curve A - Cumulative potential induced compaction from equilibrium.
B - Individual increment potential induced compaction from equilibrium.

The technique, for computation of the amount of subsidence, depends upon the assumption that the peats, which separate the intervals, were formed at 'sea level'. Most of the evidence to support this assumption is based on inference (see Wilson 1965), but some is derived from studies of modern deltas (O'Neill 1949). It is not essential that the peats were at the same level at the same time.

The induced compaction estimated for the lower intervals will be subject to some error because of the restricted amount of substrate which can be taken into account. However, as shown in figure (7.4.1), the cumulative, potential induced compaction falls rapidly with depth below the sediment surface. Below 100 increments, about 17 feet of Coal Measures shale, large increases in depth produce only small increases in cumulative potential. Therefore, the error for interval 2, the first which can be considered, may be quite small.

7.4(a) Total subsidence

The map of total subsidence, figure (7.4.2), was subjected to trend surface analysis. The trend surfaces, figure (3.0.1), show how the increasing subsidence towards the North-West is reversed in the extreme northwestern corner of the study area. This feature can be seen in many of the trend surfaces and deviation maps produced in section (6). Comparison with the map of the pre-Permian tectonic features, figure (6.7.3), suggests that reduction in amount of subsidence occurs across the Don Monocline. The monocline trends North-East to South-West and is

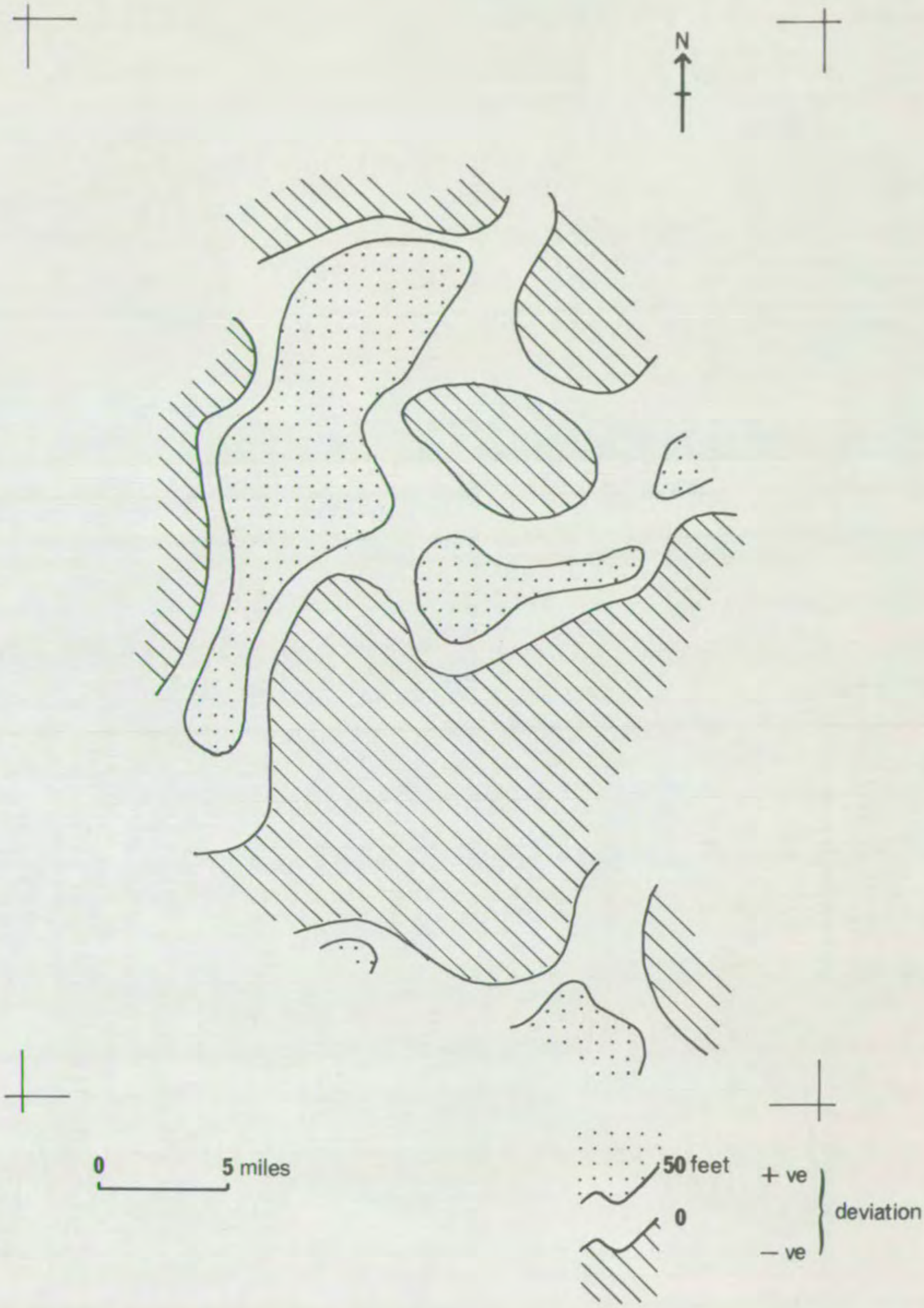


Figure(7.4.2) Cumulative subsidence necessary to emplace the section of strata between the Threequarters coal and the Clay Cross Marine Band.

thus almost orthogonal to all the tectonic lineations shown in figure (6.7.3). The absence of any other tectonic control is shown by the map of quadratic trend of trend deviations, figure (7.4.3), which consists of elongate highs and lows which cut obliquely across all the fold-hinges and troughs of figure (6.7.3). This lack of correspondence can be objectively proved by considering the serial correlation coefficients, of deviations from the trend surfaces, which indicate an East to West orientation of elongation, table (7.4.4).

The correlation coefficient between total subsidence and total thickness, table (7.4.5), and the lower bound for the population coefficient, indicate that the hypothesis of zero correlation must be rejected at all tabulated levels of significance. On the regional and large local scales, it appears, therefore, that sediment accumulation is almost entirely controlled by subsidence. The slope of the reduced major axis (1.13) and the intercept, on the subsidence ordinate close to the origin, proves the absence of control by other processes. Further proof comes from the lack of correlation (+0.07) between the total induced compaction and the deviations from the quadratic trend of trend surface. Table (7.4.5) also shows the strong positive correlations between total subsidence and thickness for individual intervals.

The correlation coefficients between peat thickness and subsidence are anomalous. While only one coefficient is significant in the comparison of individual peat thicknesses with the subsidence necessary to emplace the underlying interval, the coefficient computed between total peat thickness and total subsidence is significant at the 5% and 1% levels. The source of the anomaly appears to lie in scale at which the variance



Figure(7.4.3) Deviations from the quadratic trend of trend surface of total subsidence.

	Serial correlation coefficients			
Polynomial order	E-W	N-S	NE-SW	NW-SE
Linear	0.411	0.112@	0.181	-0.035@
Cubic	0.271	-0.138@	0.049@	-0.432@
Sextic	0.242	-0.298@	-0.057@	-0.464@
Octic	0.024@	-0.470@	-0.050@	-0.510@

Table(7.4.4) Serial correlation coefficients for deviations from trend surfaces of total subsidence ; East Midlands Coalfield.

@ coefficient less than two standard deviations greater than zero.

arises in the peat thickness data. The average relative deviation of the individual peat thickness data sets is 45% of the average mean thickness, compared to 27% for the total thickness set. If the variance of individual peat thicknesses arises predominantly on the residual scale, then on summation it is probable that many irregularities will cancel each other out, causing the relative deviation to fall. Summation, like averaging, causes the variance on the large scale to be exaggerated at the expense of the contribution from the small scale. It follows that on the regional or large local scale, peat thickness is controlled by subsidence.

This cause and effect relationship is complicated on the small scale, where strong subsidence gives rise to splitting and thinning; an example is the split of the Deep Soft Coal towards the central mound of the Deep Hard rock, section (8.3). The contrast of the strong correlation between number of cycles and total subsidence, table (7.4.5), and the weak correlation between the percentage of cycles, terminated by coals, and subsidence, suggests that while there are more opportunities for peat growth near the centre of the Pennine Basin, fewer are exploited. This is not surprising, because the subsidence rate must be proportional to the total subsidence, unless the Coal Measures' horizons are appreciably diachronous and, therefore, less time is available for peat growth near the centre of the basin.

	Total subsidence (less peat)
Total thickness (less peat)	$0.985^{@}$
Total peat thickness	$0.332^{@}$
Number of cycles	$0.540^{@}$
% cycles terminated by coals	-0.060

Total subsidence (less peat)	Total thickness (less peat)	peat thicknesses upper peat	peat thicknesses lower peat
interval 1	?	?	?
2	$0.981^{@}$	-0.056	0.095
3	$0.986^{@}$	-0.084	-0.025
4	$0.976^{@}$	-0.145	-0.077
5	$0.986^{@}$	$-0.308^{@}$	$-0.386^{@}$
6	$0.957^{@}$	-0.172	-0.035
7	$0.986^{@}$	-0.088	0.337

Table(7.4.5) Correlation coefficients between various attributes.

@ coefficient significant at 5% level

7.5 Conclusions

It has been shown that where wedges of sediment are separated by a horizon of peat, compactional studies can be conducted at equilibrium. Otherwise, the possibility that disequilibrium in the substrate can give rise to overcompaction must be taken into account. Disequilibrium arises from fast sediment accumulation.

On any scale, incoming sediment cannot be totally emplaced by the compaction it can induce in previous sediments. There is a resulting strong correlation between subsidence, not arising from compaction, and sediment thickness. On the local scale, sandstone bodies are predominantly emplaced by subsidence. Topographic irregularities cannot be passed on by differential compaction, and thus cannot be used to explain the similarities and differences between Coal Measures intervals described in section (6). Localisation of deposition can be caused by the initial overcompaction of peat in response to some overburden.

On the regional and large local scale, peat thickness is controlled by subsidence. The control is complicated by a cut-off at high subsidence rates, which are associated with large amounts of subsidence. On the small scale, the control of peat thickness can be ascribed to residual compaction arising in underlying sediments accumulated at disequilibrium, although other edaphic, hypedaphic and botanical factors must be taken into consideration.

The rate of accumulation of peat is much slower than for equal thicknesses of clastic sediment. The Pennine Basin can, therefore, be considered in terms of a peat swamp with infrequent episodes of sediment deposition.

Patterns of total subsidence, of the section of Coal Measures strata under consideration, are similar to those of the isopachs of total thickness of the Westphalian (Wills 1956). Reduction of subsidence towards the extreme North-West of the study area may possible be the result of the syndepositional activity of the Don Monocline. The distribution and orientation of deviations from the quadratic trend surface, of total subsidence, are completely unrelated to any other tectonic features, and this possible control can be discounted.

SANDSTONES

INTRODUCTION

The Coal Measures sandstones yield by far the most information regarding the depositional environment. The sandstones have been studied at two levels, gross geometry and internal geometry. The latter includes sedimentary structures and texture.

At each level comparison with recent sediments suggests possible modes of formation. However, the sandstones of tomorrow are being formed in a wide spectrum of environments. It is possible to restrict the range by taking into account two fundamental aspects of Coal Measures rocks. Firstly, interspersed coal seams and subaqueous fauna, both marine and non-marine, suggest repeated emergence and submergence and, therefore, deposition at a continental margin. Secondly, the sandstone bodies tend to be elongate. According to Rich (1923) the possible models are, offshore bar, onshore or beach bar, ordinary river channel, delta distributary and tidal channel. Delta margin cherniers or ritsen, as described by Brouwer (1952), van Andel (1967) and Allen (1964, 1965) should be added to this list, together with the larger-scale delta-front or coastal barrier sands as described, for example, by Oomkens (1967). A new category, tidal sand ridges, has been suggested by the work of Tanner (1961), Off (1963), Ball (1967) and Houbolt (1968).

Taking into account the size of the Coal Measures sandstone bodies (see for example Hoyt 1969 on the distinction of cherniers and barriers) and the possibility that the responses to processes in some models will be indistinguishable in ancient sediments (see for example van Straaten 1959 p.206), only five basic models were considered; these were alluvial plain, delta distributary, tidal ridge, barrier or offshore bar and coastal barrier sands.

The various geometrical properties of the sandstone bodies have been interpreted in terms of the palaeogeography, reconstructed in section (3) and illustrated in figure (3.0.4), within the framework of the depositional model depicted in table (8.0.1). As shown, the strong positive correlation between equilibrium peat thickness and subsidence and, therefore, total thickness, and the correspondence of areas of maximum total thickness and marine acme are not compatible with the simple conceptual intracratonic deltaic or intercratonic miogeosynclinal models proposed by Pryor (1961).

The amount of sandstone, expressed as a percentage of the total thickness, has a positive but insignificant correlation with total thickness markedly unlike the Chesterian deltaic model of Pryor. Although sandstone and total thickness have a significant positive correlation, it partly arises from the technique of testing the null hypothesis of independence of a component of its sum with two others, in a closed number system.

Table(8.0.1) Depositional model for the East Midlands' Coal Measures' sediments.

%m = marine influence ; acme of marine faunal zones.

%s = sandstone as a % of total thickness

t = total thickness in feet

s = total sandstone thickness in feet

%c = % presumably swamp organic deposits of total thickness.

model :-

$\%m = fn(t)$		
$s = fn(t)$	$r = +0.400\ (n = 73)$	$+0.19 < r(p) < +0.58$
$\%s \neq fn(t)$	$r = +0.068\ (n = 73)$	$-0.18 < r(p) < +0.31$
$\%c = fn(t)$	$r = +0.332\ (n = 73)$	$+0.10 < r(p) < +0.52$

Table(8.0.1) fn(t) = a function of, or proportional to, 't'

r = sample correlation coefficient

5% and 1% significance levels = 0.232 and 0.302

r(p) = 95% confidence band for population coefficient

n = sample size

8.1 Plan View

8.1(a) Absolute size and shape

The bodies of sandstone in the East Midlands Coal Measures are not unique in terms of their gross geometry. Parallels can be drawn with modern and ancient sands whose genesis is known or inferred.

The geometry is very variable, and it is, therefore, difficult to quote representative figures to describe the size and shape, especially since there is no convention for measurements of these parameters. The width between the zero isopachs of sandstone thickness may be up to 10 miles. However, as suggested by Potter (1962), the 20 feet isopach may be used to define "channel" trends. The width on this basis is commonly only 3 or 4 miles.

The maximum thickness recorded for a single sandstone was 165 feet but more typical values lie between 90 and 100 feet. The maximum continuous length was 25 miles, although this is a minimum figure because the evidence has been destroyed by erosion in the West and is lost through lack of control in the East.

The overall similarity to data from the Carboniferous of Illinois (Potter 1962) is probably insignificant because of the wide range of this data. The gross geometry of the American sandstones is that of supposedly alluvial valleys in which they were deposited. Alluvial plain deposits tend to be less restricted in width (Schlee et al 1960, Shelton 1967). This fact is corroborated by studies of modern meander valleys, for example the alluvial plain of the Rio Grande (Nanz 1954) which is 10 miles and more across.

Shelton (1967) implied that it is possible to differentiate alluvial and bar sands on the basis of the ratio of length to width; the ratio is much smaller in the former than the latter. The need for a careful definition of the term "alluvial" can be seen by comparing Shelton's ratio to Rich (1923), who concluded that "Offshore bar is suggested for many of the lenticular sand bodies ..... which do not have the distinctive narrowness of beach and channel deposits."

The length to width ratio must be considered with respect to the absolute size. For example the cherniers or ritsen of the Suriname coastal plain (Brouwer 1953), while having ratios correctly indicating that they are bars, are usually less than one fifth of a mile wide. The Coal Measures sandstone belts, therefore, can hardly be considered as ritsen whatever their ratio of length to width. The coastal barrier sand of the Rhone Delta (Oomkens 1967) is about 50 miles long and ranges between 2 and 17 miles wide, therefore comparing well with the sandstone belts. Some examples are listed in table (8.1.1). Apart from the Meridian sand, which is Eocene in age, most of the offshore bars of table (8.1.1) tend to be narrower than the East Midlands belt sandstones. Similarly, tidal sand ridges, as described by Houbolt (1968) and Sheldon (1968), are rarely more than two miles wide.

Table(8.1.1) Dimensions of some barrier islands (bi) and off-shore bars (ob).

locality	data source		l	w	t	type
Niger Delta	Allen(1965)	av.	11	5.0	?	bi
		max.	22	8.0	?	bi
Orinoco Delta	van Andel(1967)		30	7.0	?	bi
Choctawatchee Bay	Hyne & Goodell(1967)	min.	5	1.0	20	bi
		max.	10	2.0	?	bi
Gulf of Mexico	Shepard(1960)	max.	100	20.0	100	bi
Fresian Islands	Price(1963)	av.	15	3.0	?	bi
Brazil	Shepard(1960)	max.	140	20.0	?	bi
		av.	?	6.0	?	bi
New Jersey	Bass(1936)	av.	8	2.0	?	ob
Florida	Hyne & Goodell(1967)	min.	5	1.0	?	ob
		max.	10	2.0	?	ob
Bahamas	Ball(1967)	av.	?	1.0	?	ob
Eagle Sandstone	Shelton(1967)	min.	40	20.0	50	bi
		max.	?	30.0	100	bi
Meridian Sandstone	Wermund(1965)	av.	80	12.0	100	ob
Kansas Shoestrings	Bass(1936)	min.	1	0.5	50	ob
		max.	7	1.5	100	ob
Garnet Shoestring	Rich(1923)	min.	8	0.25	?	ob
		max.	?	0.75	50	ob
Colony Shoestring	Rich(1923)	min.	9	0.5	50	ob
		max.	?	0.75	100	ob

Table(8.1.1) l = length, miles ; w = width, miles ; t = thickness, feet ;
av = average ; min = minimum ; max = maximum

Continuous lengths for the Coal Measure sandstones range from 5 miles for pods above the Roof Soft Coal to 25 miles for the Deep Hard Rock. In comparison, barrier islands tend to be continuous for tens of miles, whereas offshore bars are often individually less than ten miles but their chains may extend for more than 100 miles. Tidal bars can be 20 or 30 miles long but are usually only 6 or 7 at most.

If extensive continuity is not an important factor in separation of bar types, its absence is critical evidence against an alluvial or bar finger mode of origin. Continuity of the 20 feet isopach is the minimum requirement. Similarly, although the widths of Mississippi bar fingers, about 6 miles, are comparable with the sandstone belts the largest, the South-West Pass, stretches only 20 miles from its mouth to the head of passes (Fisk 1961).

In conclusion, it appears that although size alone may be ambiguous as an indicator of depositional environment, discontinuity at the 20 feet isopach level strongly argues against an alluvial or bar finger origin. Bars, however, exhibit a range in continuity embracing all the Coal Measures examples. Delta-front sands can probably be formed on all scales but, on average, offshore bars are narrower than the sandstone belts.

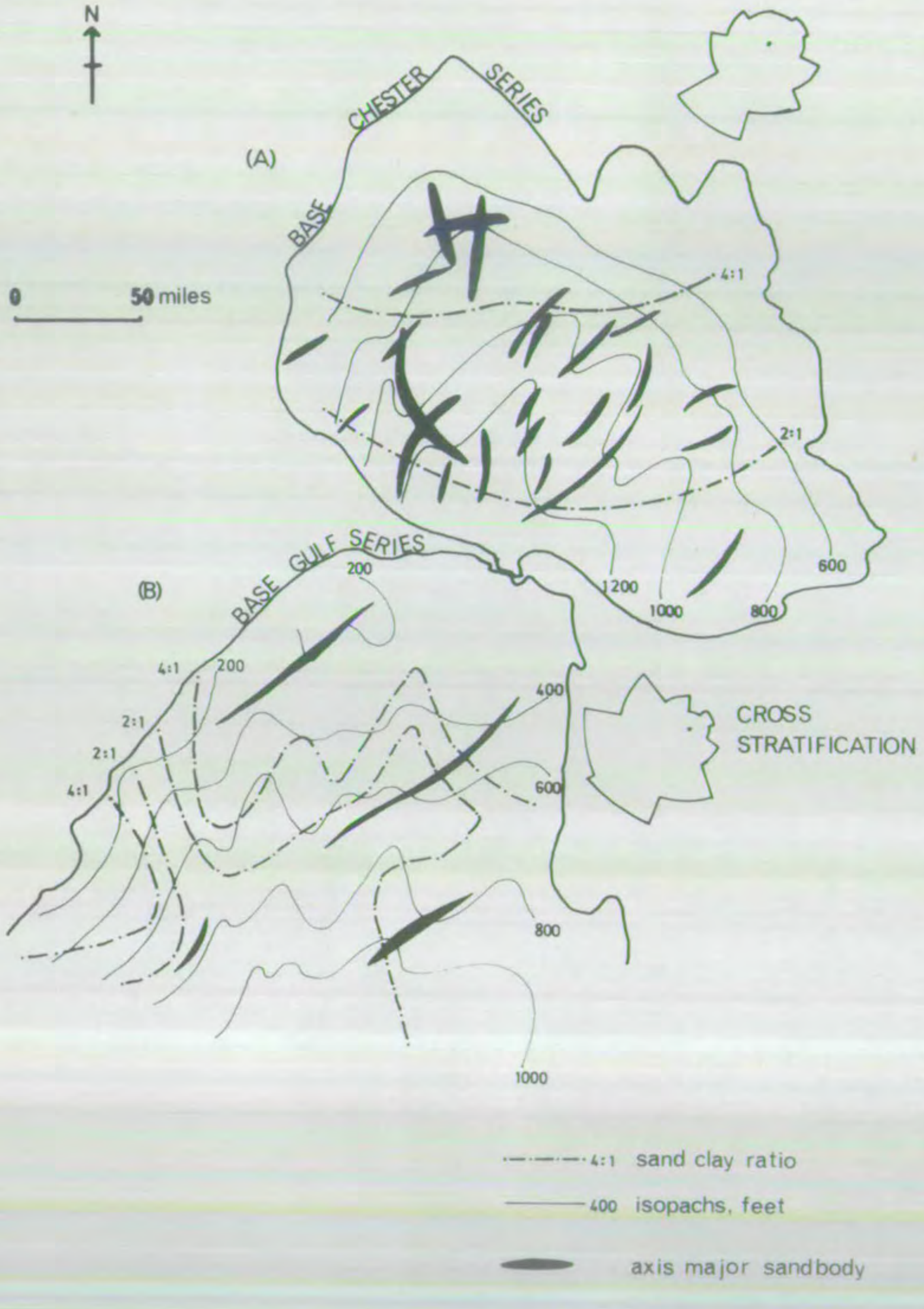
8.1(b) Patterns of sandstone belts

Care must be taken when considering the patterns of the belt sandstones, shown in figures (4.2.2) to (4.8.3), to ensure that comparisons are made on the correct scale. For example, the absence of common branching and sinuosity cannot be taken as significant evidence against an alluvial origin because the sandstone belts are on the scale of the alluvial plain.

Comparison of map size and control density with Fisk's (1961) illustrations of the Mississippi Delta shows that only an occasional branch would be expected if the sandstone belts were formed as distributaries. However, considered in the same way, the ancient delta complex of the Booch Sandstone (Busch 1953) suggests that multiple branching would be the rule.

Barrier islands, offshore bars and delta-front sands do not branch, and tend to be straight or slightly curved. Similarly, tidal ridges do not branch but do have a tendency to occur in groups. Off (1963) found a relationship between ridge height and the lateral displacement between individuals in the group. Using an approximate value of 100 feet for the maximum belt thickness and, therefore, ridge height, the maximum lateral displacement should be about 10 miles. The Coalfield covers a distance of about 40 miles in a direction orthogonal to the belt axes, and thus any sandstone belt should have at least two neighbours. Occurrences of this phenomenon are rare and can usually be shown to be diachronous (see section 8.3).

In conclusion, the pattern of sandstone belts does not appear to be a critical factor in deciding the depositional environment. However, the tidal ridge model is not favoured by these results and the absence of any certain contemporaneous branches suggests that alluvial and delta distributary models are less likely than a bar or delta-front sand hypothesis.



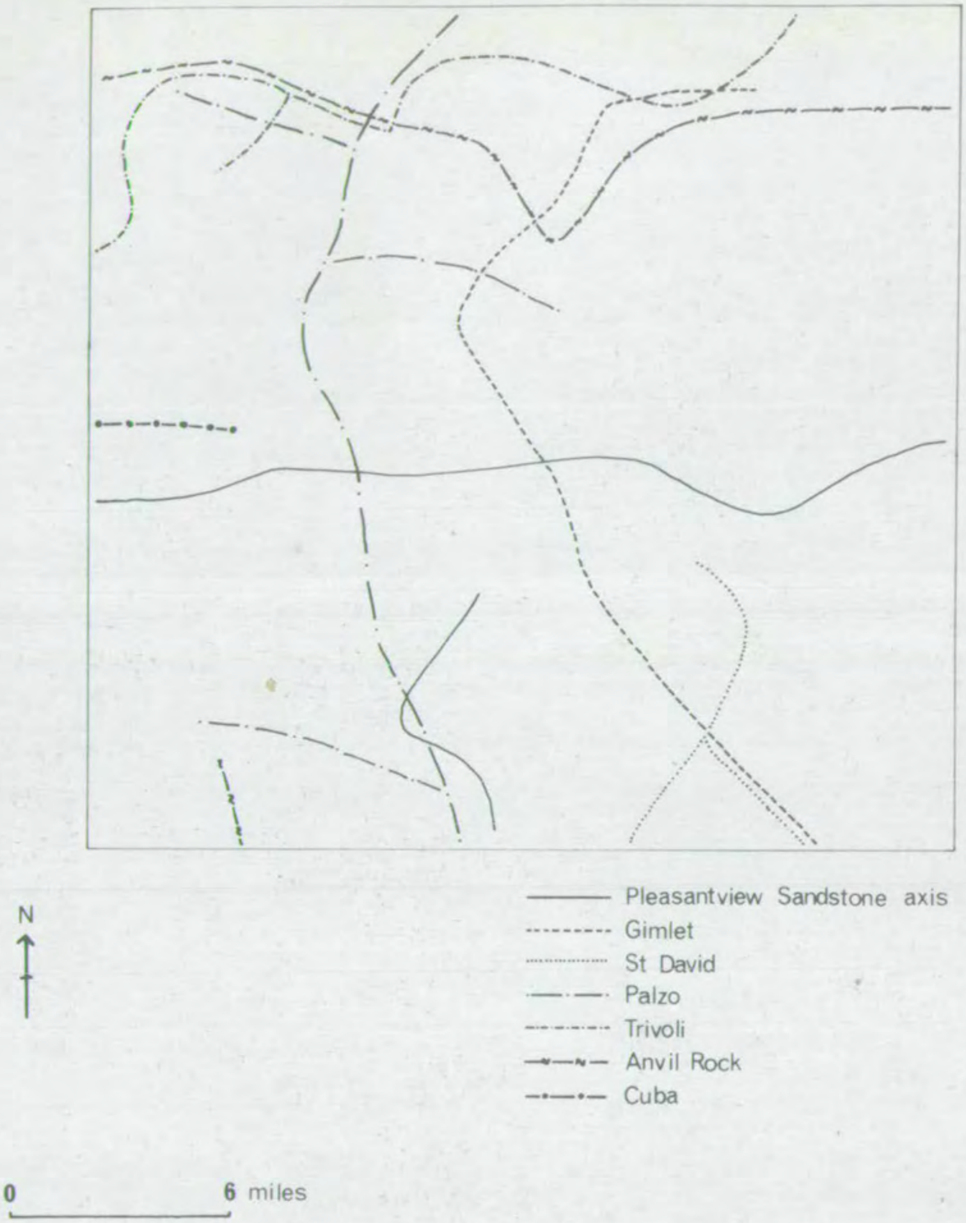
Figure(8.2.1) and Figure(8.2.2) (A) and (B) respectively.

8.2 Orientation of Sandstone Bodies

Since the early part of the 20th century, it has been thought that alluvial and bar sands could be distinguished on the basis of their orientation relative to the shoreline. Pryor's (1961) rather oversimplified models, shown in figures (8.2.1) and (8.2.2),[Δ] outline the concept. However, to what extent this is a noumenon rather than phenomenon can only be judged statistically.

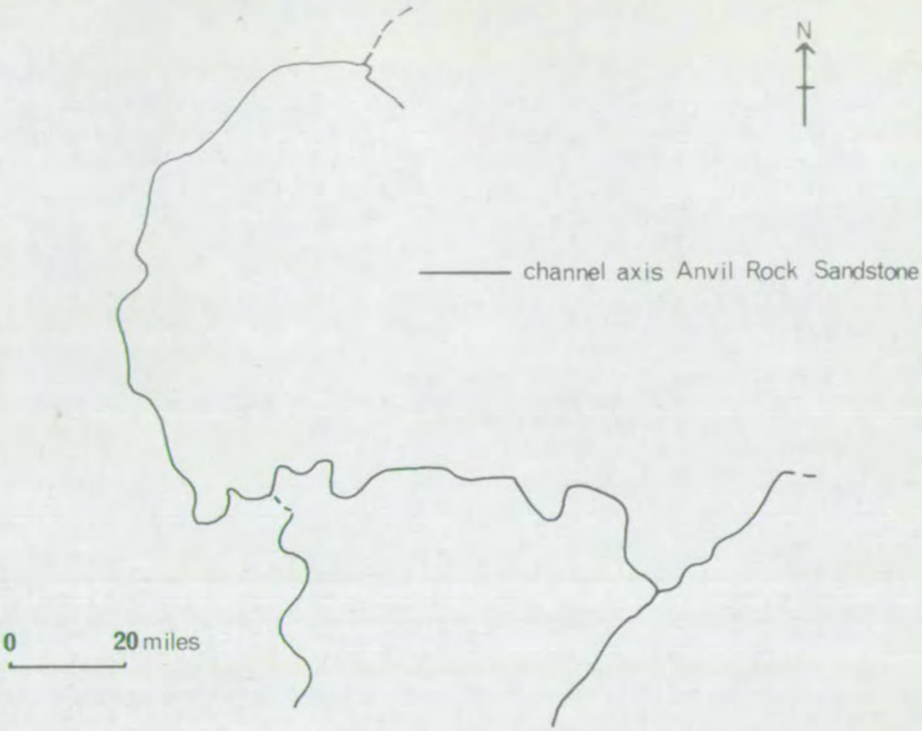
Although bars are usually reasonably consistent in their relative orientations, alluvial deposits can have variable trends. A classic example, after Mueller et al (1957), is shown in figure (8.2.3). Seven presumably alluvial "channels", from about the same stratigraphic range in the Pennsylvanian of Illinois as is under investigation in the Westphalian of central England, appear to have two distinct trends directed at right angles to each other. Another example can be seen in Pryor's (1961) figures 3 to 7,[Δ] although the text declares the opposite! Variability arising for one particular sandstone can also be extreme. Two examples from the Anvil Rock (Potter and Simon 1961, figure 2) and Trivoli sandstones (Andresen 1961, figure 15, open circles) are shown in figures (8.2.4) and (8.2.5). Deflections by obstructions, which are often bars, can be seen in the recent sediments of the Niger Delta (Allen 1965) and the Pleistocene of the shelf sediments of the Gulf of Mexico (Curray 1960). Perhaps in the face of this variability, Potter and Pettijohn's (1963) comment may be an understatement: "Elongate fluvial sand bodies,

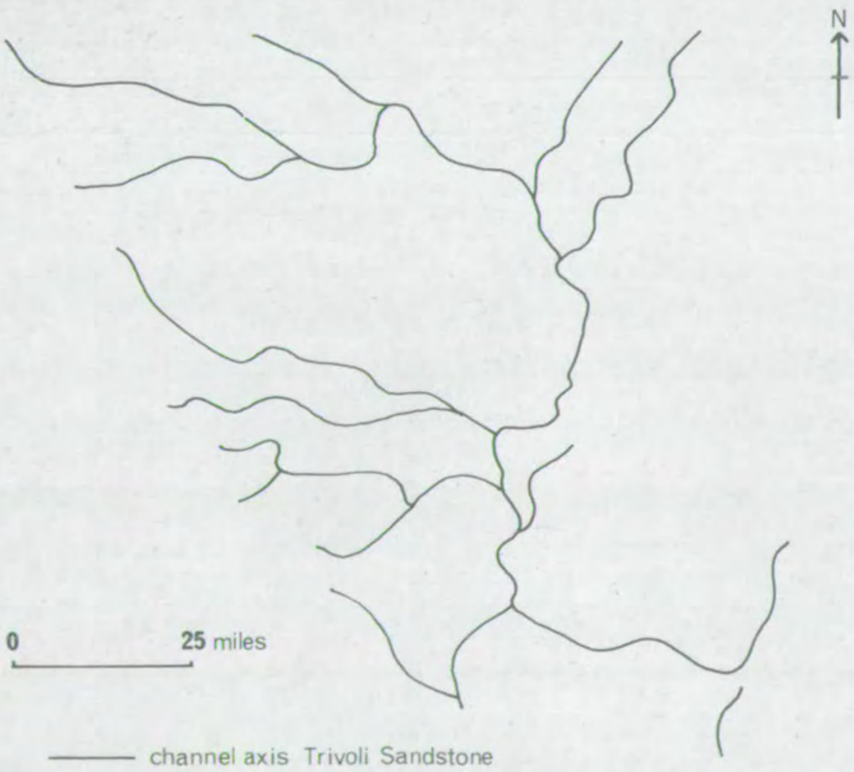
Δ fig. ref. out of place



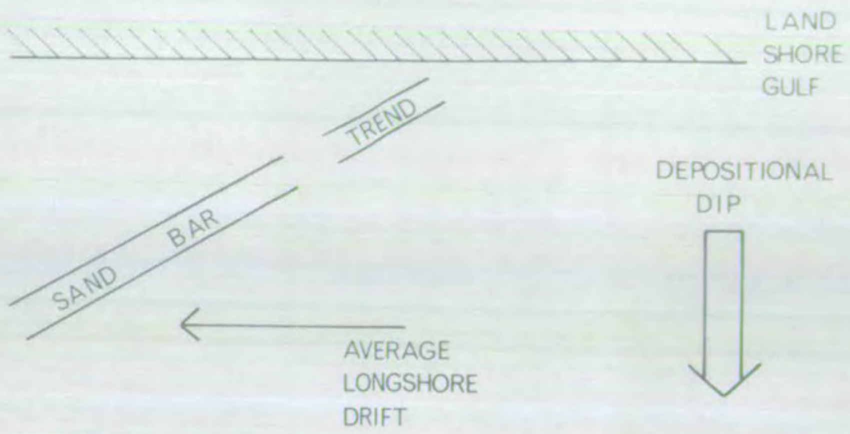
Figure(8.2.3) Trends of sandstone body axes in Illinois ; after Mueller and Wanless (1957).

Figure(8.2.4)

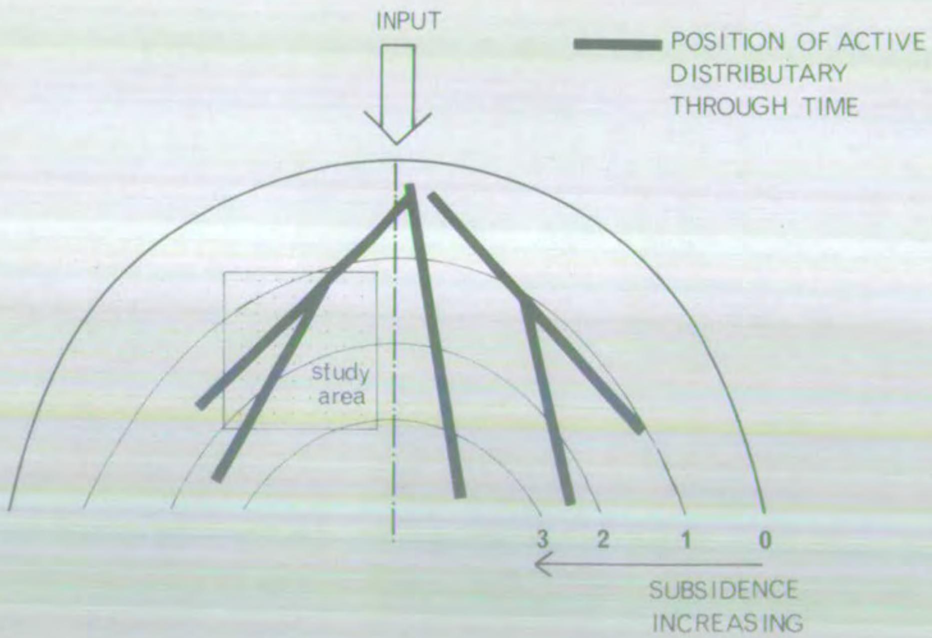




Figure(8.2.5)



Figure(8.2.6) Conceptual model of the orientation of off-shore bars relative to the shoreline.



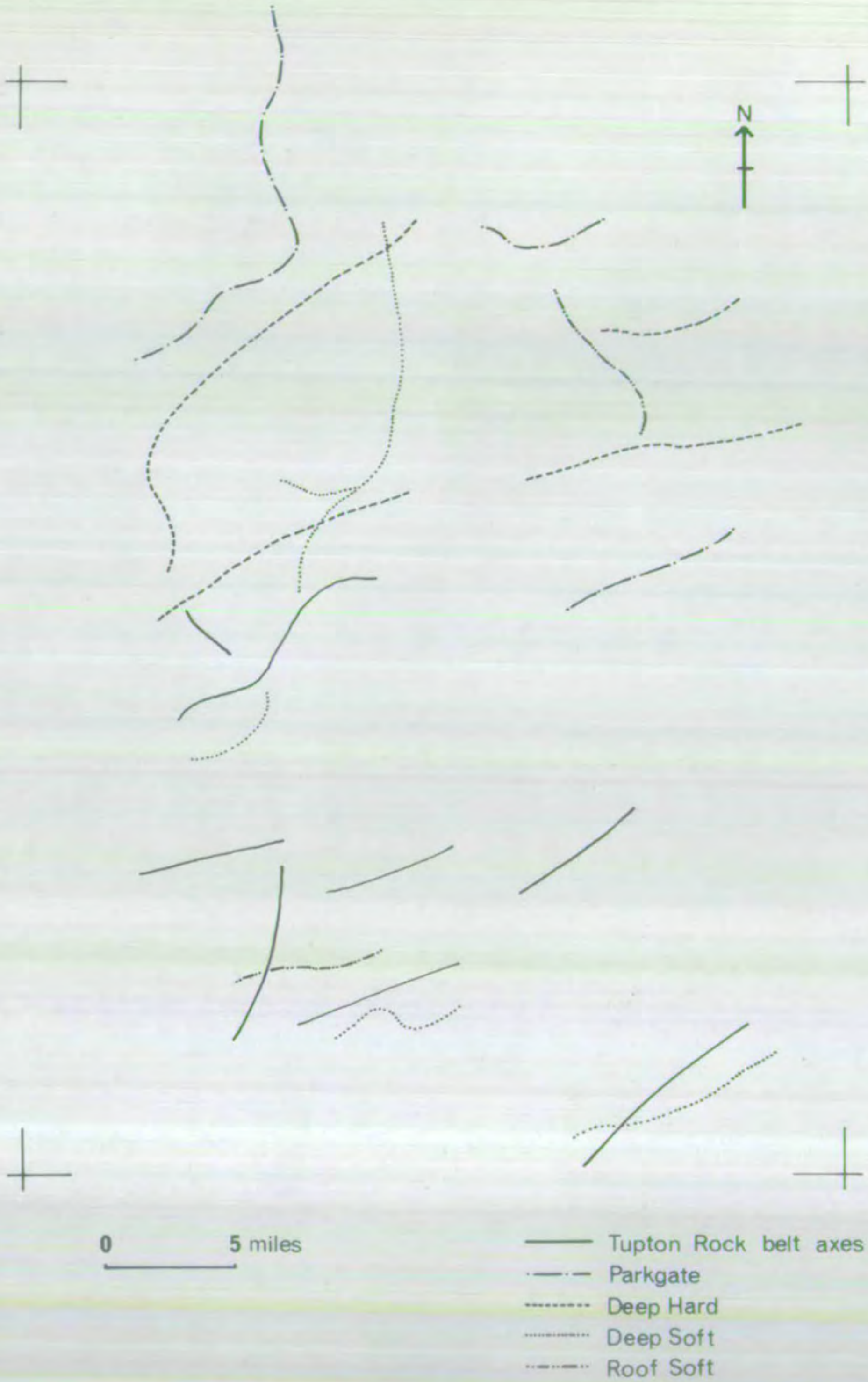
Figure(8.2.7) Conceptual model for the growth of a Mississ-ippi type delta into a partly enclosed basin.

as part of a regional fluvial or deltaic system, are commonly perpendicular to the depositional strike, although many local deviations are known."

Excluding the obvious example of beaches, bars show a remarkable parallelism with shorelines. This characteristic is shown in open shore environments (Shepard 1960) and fringing deltas (Allen 1965, van Andel 1967, Oomkens 1967). However, the parallelism is statistical rather than substantive. En-echelon grouping is typical and arises from oblique growth, as demonstrated by Hyne and Goodell (1967) off the coast of Florida. The displacement, which can be as much as 25°, only operates in one direction along any particular shoreline, since it is a result of the direction of average longshore drift. The model is shown schematically in figure (8.2.6).

Tidal sand ridges are orientated parallel to ebb and flow directions and, therefore, there is no genetic link with the depositional dip. Along the European and English coasts of the North Sea, ridges sub-parallel to the shore have been described by Houbolt (1968) and others almost perpendicular by Sheldon (1968).

It follows that in a study of an ancient system, great variability in direction of elongation, with no statistical relationship to the depositional dip or strike, suggests a tidal ridge. A mean perpendicular to the strike but with large variance suggests an alluvial or bar finger origin. However, in the latter case there is a problem of scale. If the study area is large enough to contain the whole delta the above criteria will apply; if, on the other hand, only part of the delta is included, especially where the area lies wholly on one side of the bisectrix



Figure(8.2.8) Orientation of sandstone belts in the East Midlands Coalfield.

drawn at right angles to the coast, then the variance could be quite small. In this special case it is also possible that the distributaries could be subparallel to the depositional strike. This model is shown diagrammatically in figure (8.2.7), for the case of a partly enclosed basin.

Finally a small variance and statistical correspondence with the depositional strike indicates that the sandstone body was deposited as a barrier or offshore bar, or delta-front sand.

Comparison of the axes of maximum thickness, of the sandstone belts of the East Midlands Coalfields, with the assumed depositional strike, as shown in figures (8.2.8) and (3.0.4), does not show any remarkable parallelism. In general the belts seem to be oblique to the strike, but all are deflected the same way.

Random samples were obtained from both figures by measuring orientations at intersections with the national grid at spacings of 10,000. The data sets were then grouped into classes 30° of arc in width.

The mean of the population of belt axis orientations was 64° East of North and the standard deviation 35°. A general impression gained from the literature suggests that this variance is comparatively small. The frequency distribution can be shown to be normal, table (8.2.9), and, therefore, the probability of a belt axis being directed towards the North and East, the approximate depositional strike, can be evaluated as 0.76.

The two basic concepts of parallelism and orthogonality were more rigorously tested using the chi-square statistic. Two problems inherent in this technique suggest that the results may not be entirely reliable. Yule and Kendall (1958) stated that the minimum total

Table(8.2.9) To test for the normality of the distribution of orientations of sandstone belt axes. $\chi^2_{.05}(1)$ is 3.84.

group limit (x)	(x-64)/35	cumulative normal frequency	theoretical relative frequency	e	o	$(o-e)^2/e$
-infinity	-infinity	0.0000				
			0.0336	1.1	0	0.05
0°	-1.83	0.0336				
			0.1324	4.4	5	
30°	-0.97	0.1660				
			0.2902	9.6	11	0.20
60°	-0.11	0.4562				
			0.3142	10.4	12	0.20
90°	+0.74	0.7704				
			0.1748	5.8	2	0.89
120°	+1.60	0.9452				
			0.0479	1.6	2	
150°	+2.46	0.9931				
			0.0064	0.2	1	
180°	+3.31	0.9995				
			0.0005	0.0	0	
+infinity	+infinity	1.0000				
			1.0000		33	1.34

'64' = mean of orientation sample ; '35' = standard deviation of sample

e = theoretical frequency ; o = observed frequency

frequency should be 50 and the minimum cell frequency of the theoretical population should be 5 and preferably 10. Although the first requirement is fulfilled, extensive grouping could not always meet the second. The analyses are, therefore, shown in grouped and ungrouped forms.

Table (8.2.10) shows the data used to test the null hypothesis of independence of orientations and samples, in this case belt axes and depositional strike. The ungrouped result of 14.4 infers that the null hypothesis must be rejected at the 5% level of confidence, although it is not possible to be 97.5% sure that the differences do not arise merely by chance. In other words, the degree of parallelism is just below the normal level of acceptable significance. The grouped result of 9.85 suggests that it is not possible to be 99.5% sure that the differences do not arise by chance.

Table (8.2.11) shows the data used to test the null hypothesis of independence of orientation and sample, in this case belt axis and depositional dip. To facilitate the procedure, the dip groupings were considered in an up-palaeoslope direction. The result of 61.0 shows that the hypothesis must be rejected at all tabulated levels of significance. Orientation is, therefore, not independent of sample and there must be a significant difference between the populations. The data could not be grouped for a repeat test.

The statistical similarity in orientation of the sandstone belt axes with the depositional strike and the restricted variance suggest that the alluvial and tidal ridge models must be rejected. The systematic deflection cannot readily be explained in terms of a delta-front

a) Ungrouped data

class limits	strike frequency	axis frequency
330 to 359	1	0
0 to 29	22	5
30 to 59	16	11
60 to 89	12	12
90 to 119	0	2
120 to 149	0	2
150 to 180	0	1

b) Grouped data

class limits	strike frequency	axis frequency
330 to 29	23	5
30 to 59	16	11
60 to 180	12	17

Table(8.2.10) Data to test the null hypothesis that orientation and sample, belt axis and depositional strike, are independent.

Ungrouped data

class limits	dip frequency	axis frequency
0 to 29	0	5
30 to 59	0	11
60 to 89	1	12
90 to 119	22	2
120 to 149	16	2
150 to 180	12	1

Table(8.2.11) Data to test the null hypothesis that orientation and sample, belt axis and depositional dip (-180°), are independent.

hypothesis but in the half delta model described above bar finger sands could have this tendency if the source lay to the South-West.

The model which fits all the information best is a barrier or offshore bar. The repeated deflection could be due to a prevailing longshore drift and ultimately to the prevailing wind, since it is unlikely that the basin was oceanic (Kuenen 1950). The average longshore current should, therefore, flow from North-East to South-West (Hyne et al 1967). However, sedimentary structures suggest current flow towards the East-South-East (section 8.9). This paradox can be explained by reference to Ball (1967), who has shown that reworking of the sediment is primarily the work of storms but that bar growth is controlled by drift. There is no reason why the main storm path and average longshore drift direction should coincide.

8.3 Transverse Vertical Sections

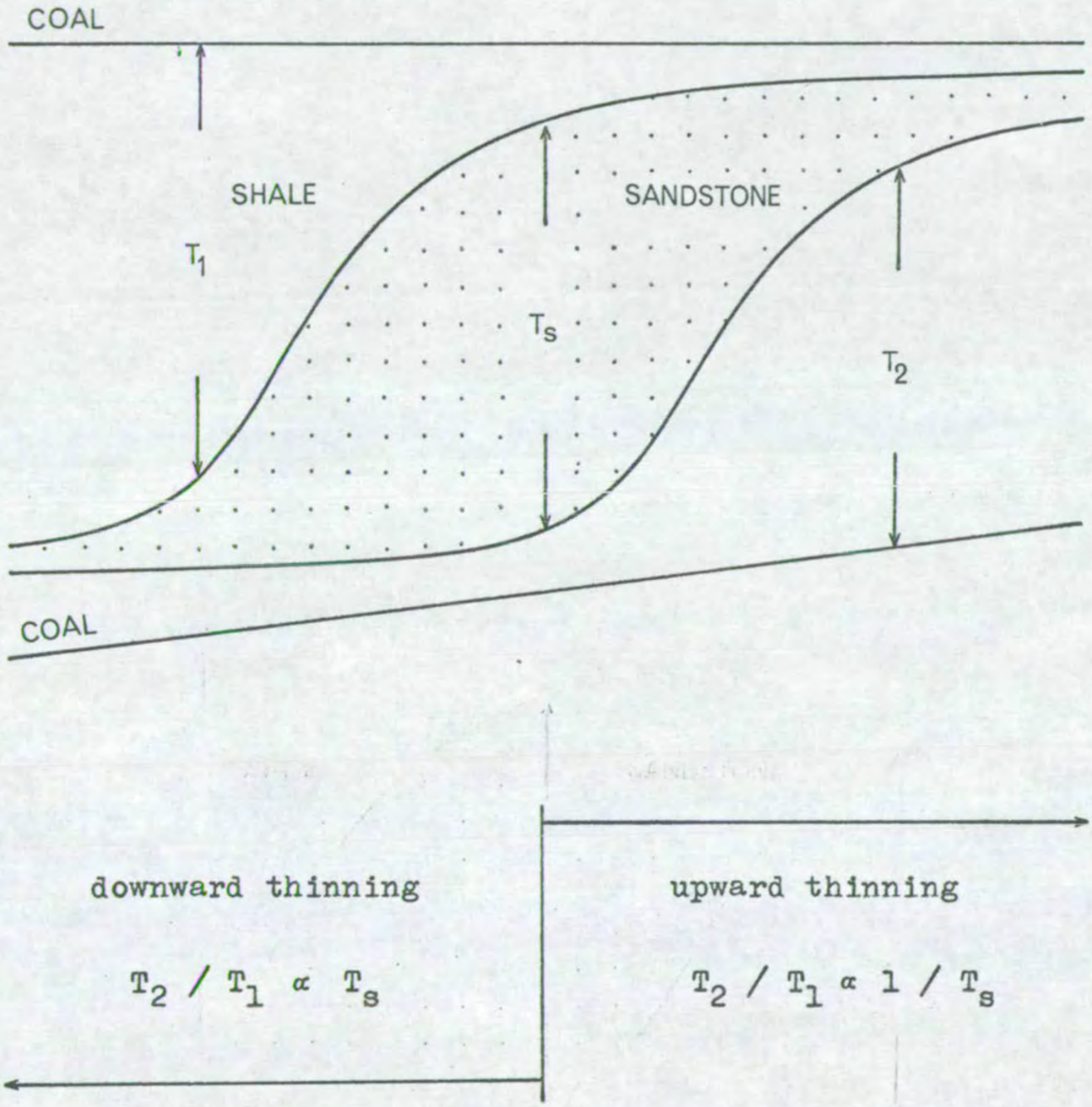
8.3(a) Shape and thinning

Time horizons cannot be constructed linking the sandstone bodies with the encompassing sediments, and it is, therefore, impossible to draw realistic cross-sections showing the depositional system and effective topography. The best approximation is made by hanging the section from an overlying datum; although this type of section shows the body shortly after formation, it compensates for any variability in syndepositional subsidence. It is not necessary for the datum to have been a time horizon or even that it was ever horizontal, since thinning criteria refer to the relative displacements of the upper and lower margins of the sandstone body from the overlying datum.

Rittenhouse (1961) pointed out possible ambiguities that can arise in studies of sandstone geometry. The selection of the marker horizon, together with the effects of compaction, were considered sufficient to completely mask the original geometry. To overcome these problems, all sections are shown in their partially compacted states, representing the subsurface geometry at the time of the formation of the overlying datum.

In a cross-section of a sandstone body, the two significant features are the relationship of the separation of the base of the body from the datum to its thickness, and whether the body thins towards the upper or lower datum. These factors are not entirely independent, figure (8.3.1).

Rich (1923) stated that onshore and offshore bars thicken upwards, and in this was supported by Busch (1961) who stated that they thinned downwards. Although the terminology is obscure, the inference of construction by the mounding of sand is clear. Cross-sections of bar finger sands from the Mississippi Delta (Fisk 1961) show a tendency to thin symmetrically towards the centre of the sediment pile. Carboniferous sandstone bodies in the U.S.A., which are supposed to have their geometry controlled by alluvial processes, thin upwards. However, there appears to be no information available on the thinning of modern alluvial deposits.



Figure(8.3.1) A hypothetical section drawn down the depositional slope, vertically through an elongate sandstone body which trends along the depositional strike; to show the two possible

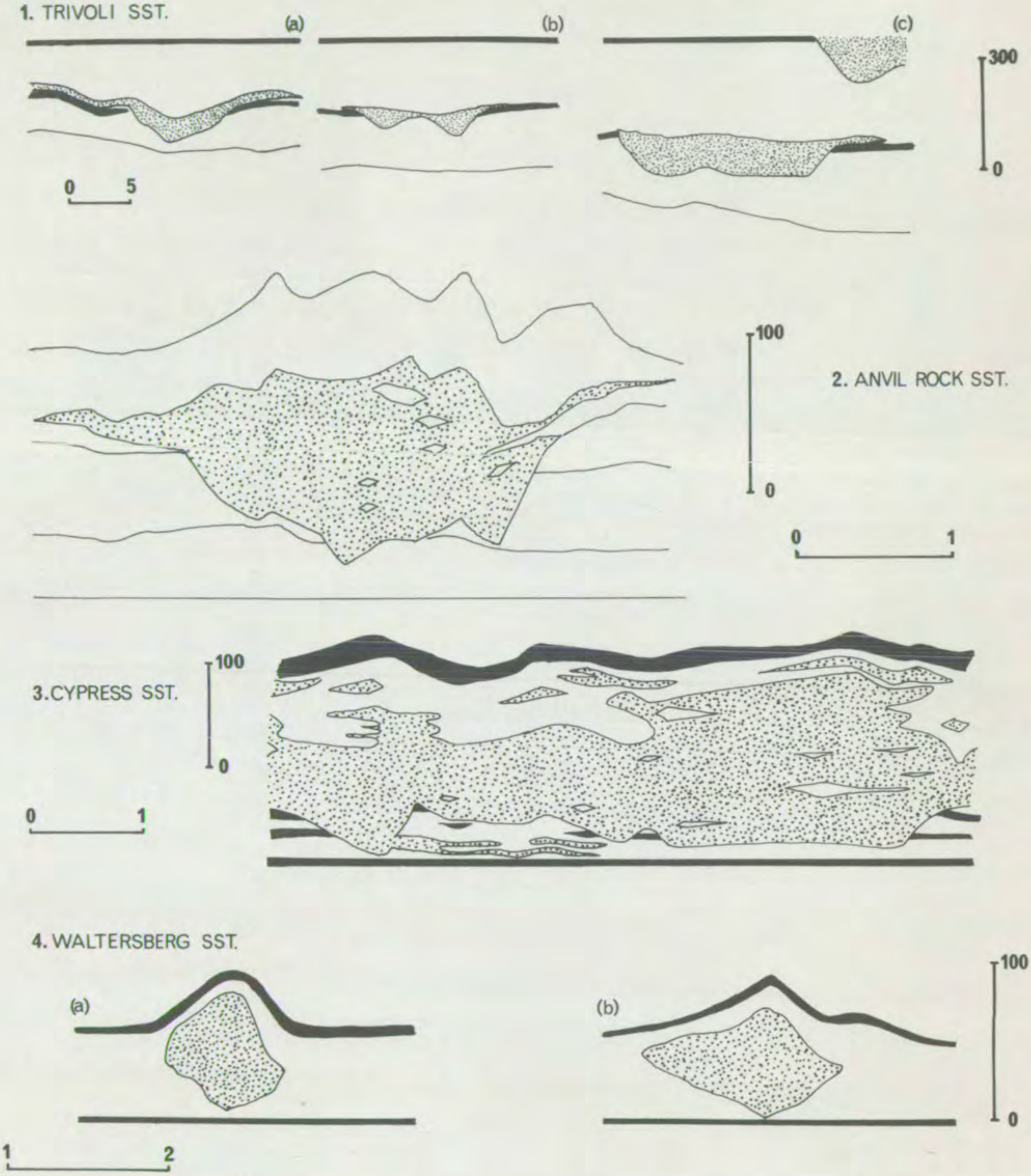
Although a flat base, parallel to the underlying datum, is supposedly characteristic of bars, some workers maintain that it is also a feature of alluvial and distributary sands; these opinions, however, are confined to the Carboniferous of the U.S.A. and as such are discussed in section (8.4).

The three-dimensional geometry of tidal sand ridges is insufficiently known to be able to make any generalisations about their thinning characteristics. However, since the ridges are formed by the mounding of sand, they will presumably have flat bases and, if buried under later sediments, should thin downwards.

The coastal barrier sands of the Rhone Delta (Oomkens 1967) have flat transitional bases but occur as sheets with only localised zones of thickening. Individual sand bodies up to 200 feet thick have been reported from the Eocene of Texas in delta-front facies (Fisher et al 1969).

The thinning characteristics of sand bodies, therefore, only permit certain conclusions to be reached. If a body has a flat base and thins downwards, it is more probable that it was formed as some kind of bar, or possibly a tidal ridge, than as a delta distributary or alluvial deposit; if, however, it thins symmetrically upwards or centrally then the bar model must be discounted.

This rather simple picture is complicated by the fact that bars rarely have flat bases. Bass (1936) used the fact that bars tend to have bases which climb stratigraphically towards the shore as diagnostic for their recognition in ancient deposits. Some care must be taken in applying this criterion. Hollenshead et al (1961) and Weimer (1961) have described bar complexes which climb stratigraphically away from the



Figure(8.3.2) "Channel" sandstones from the U.S.A.

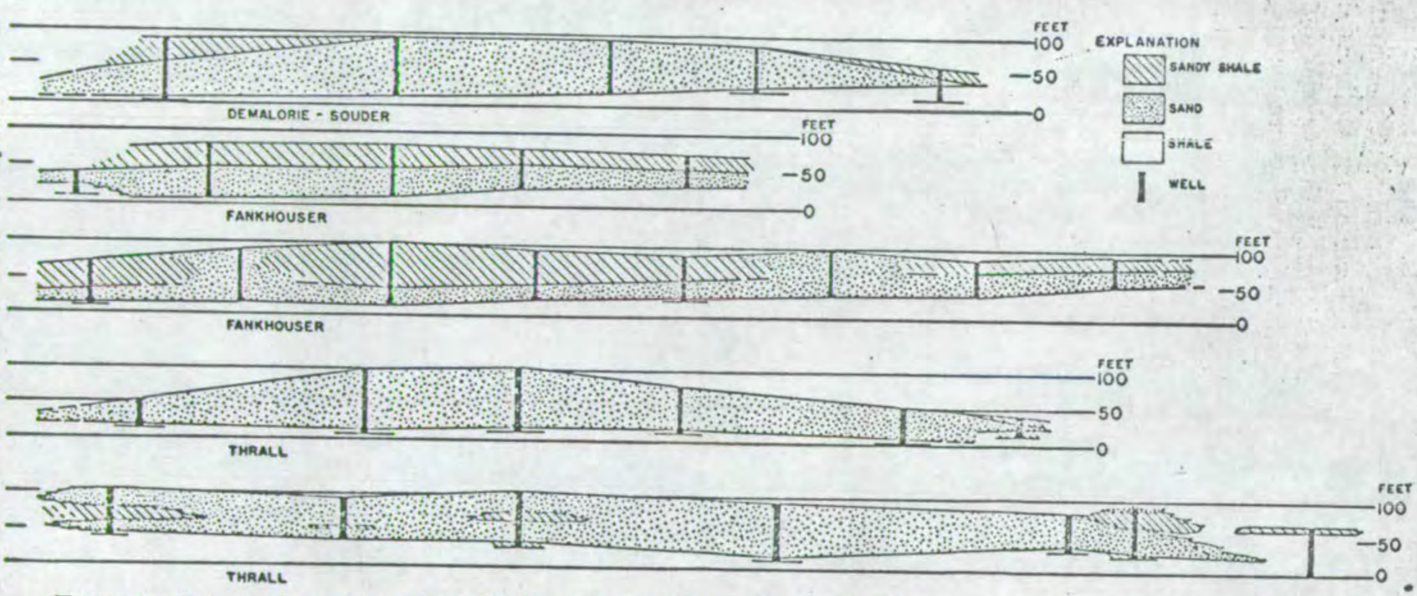


FIGURE 3. Cross sections of several sand bodies. The DeMalorie-Souder oil field cross section extends from the SE cor. NE¼ NE¼ sec. 11 to the SW cor. NE¼ SW¼ sec. 1, T. 22 S., R. 10 E. The upper of the two Fankhouser oil field cross sections extends from the NE cor. SW¼ NW¼ sec. 4, to the NE cor. of the SW¼ NE¼ sec. 4, T. 22 S., R. 12 E. The lower Fankhouser section extends from the NE cor. SE¼ sec. 5, to the NW cor. NE¼ SE¼ sec. 4, T. 22 S., R. 12 E. The upper of the two Thrall oil field cross sections extends from the SE cor. of the SW¼ sec. 29, to the SE cor. of the NE¼ of sec. 32, T. 23 S., R. 10 E. The lower of the two Thrall sections extends from the SE cor. sec. 30 to the NW¼ SE¼ sec. 32, T. 23 S., R. 10 E.

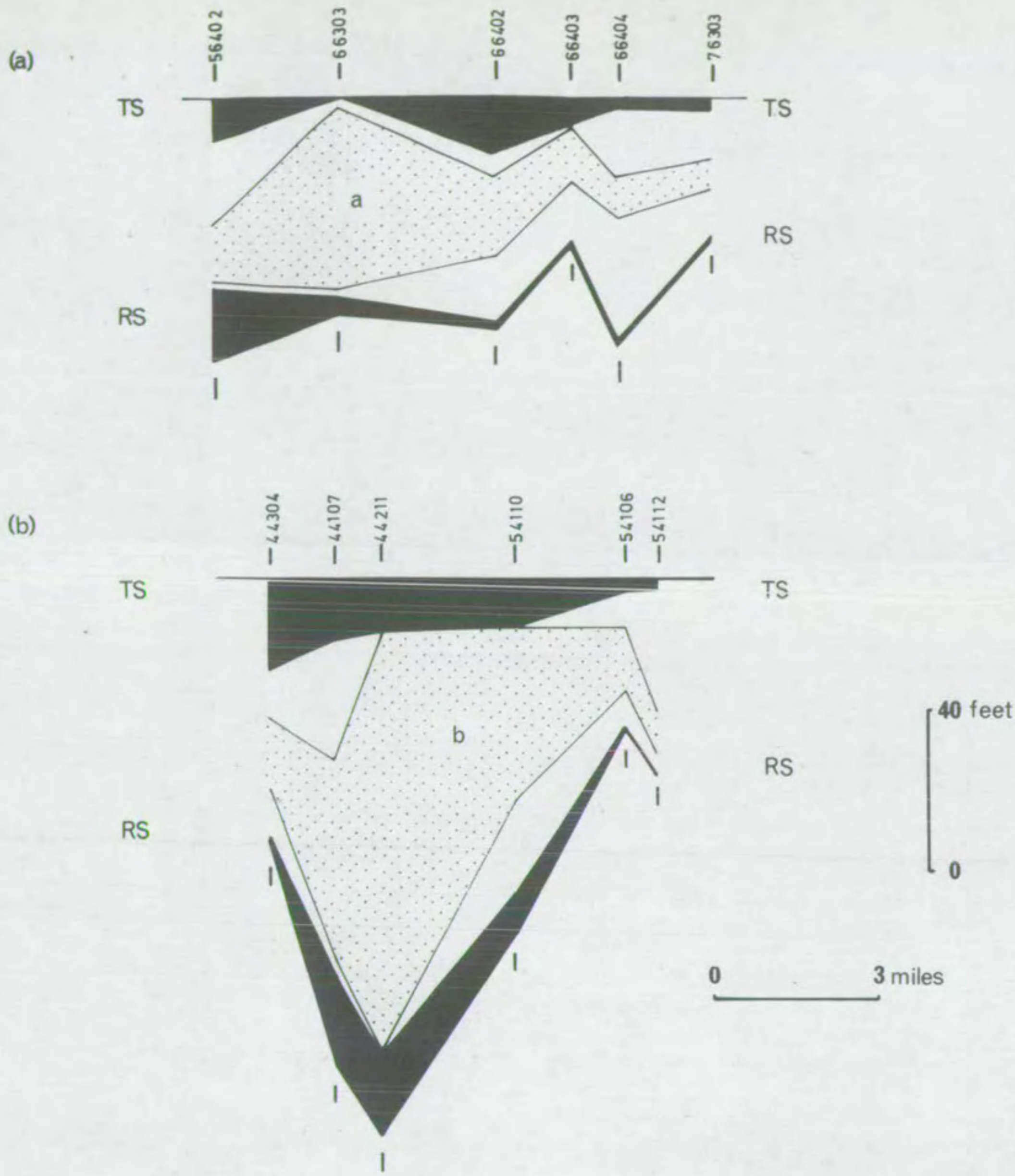
Figure(8.3.3) Transverse vertical sections of sandstone bodies showing downward thinning ; from Bass(1936).

the shore over marine deposits. Since these complexes consist of a number of small sand ridges connected by sheet sands, they cannot be directly compared with the Coal Measures sandstones.

Many of the characteristics described above are illustrated in figure (8.3.2), taken from Andresen (1961) and Potter (1963) for alluvial sandstones and figure (8.3.3), taken from Bass (1936) for barrier bar sandstones. Since thinning is an important and complex feature, sections through the Coal Measures sandstones are discussed below at some length.

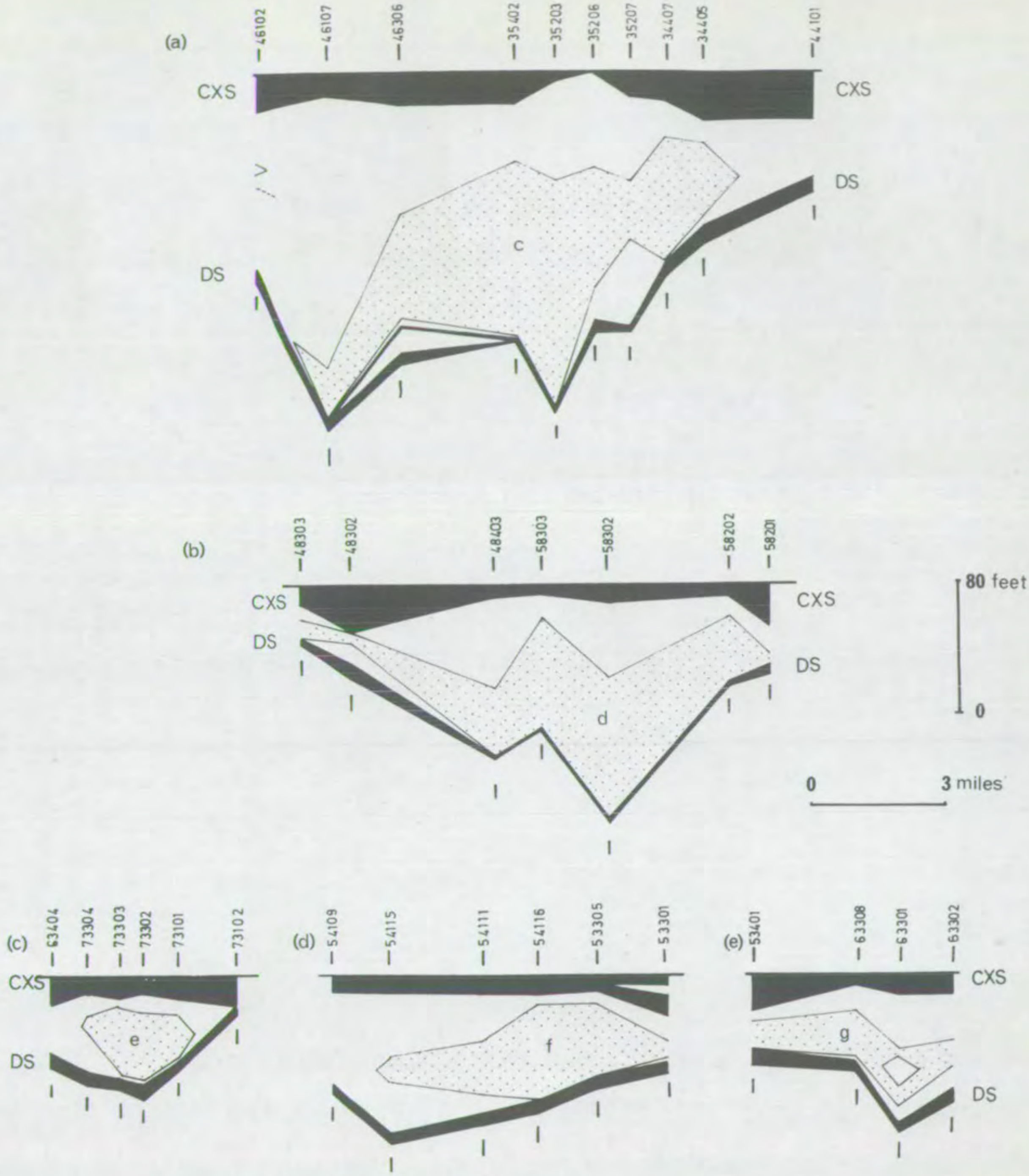
Two sections were drawn across the Roof Soft Rock. Figure (8.3.4) shows rock 'a' which thickens upwards into a central mound from the western end of the section, but thins centrally towards the South as the base lifts off the Roof Soft coal. The section is reminiscent of a bar with a base climbing stratigraphically towards the Midland Barrier. Rock 'b', figure (8.3.5), thins upwards in one direction and downwards in the other. However, the section is composite and the connection of 44211 and 54110 may not be of great geological significance, since they both lie in the axis of maximum thickness.

Five sections were constructed through the Deep Soft Rock. Whereas the base of rock 'c', figure (8.3.6), lies close to the Deep Soft coal, the separation of the top from the Roof Soft coal varies inversely with the thickness of the sandstone body. The early formation, together with later burial, is difficult to reconcile with any alluvial model but readily explicable by deposition as a bar. Like 'c', rock 'd', figure (8.3.7), has a pronounced central mound and thins away downwards. However, these features are partly obscured by the close correspondence of interval and sandstone thickness. To a greater extent, the same is true



Figure(8.3.4) (a) ; Figure(8.3.5) (b)

Transverse vertical sections through the Roof Soft Rock. For key see figure(8.3.2).

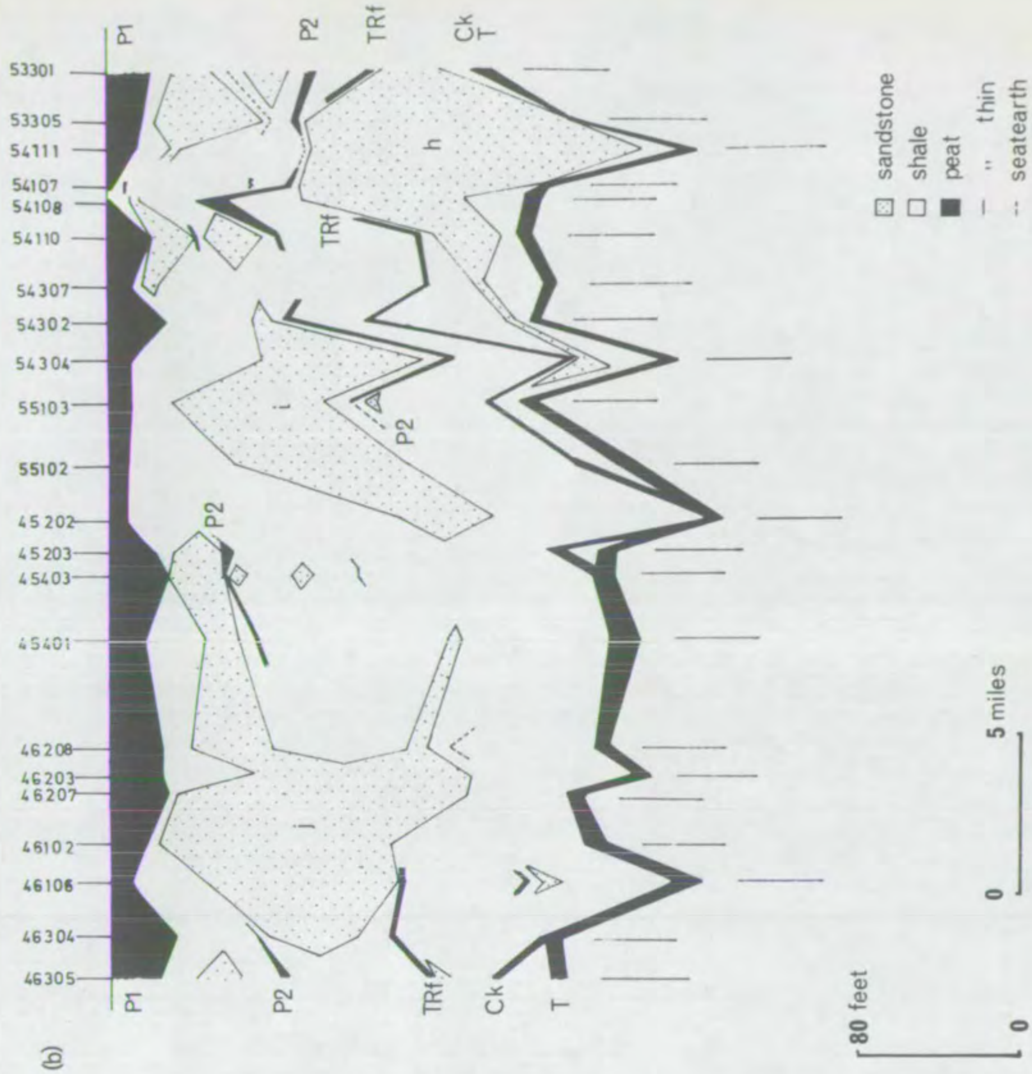


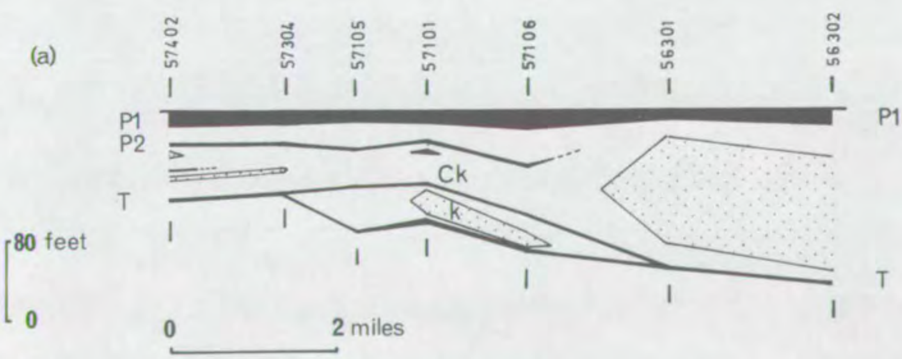
Figure(8.3.6) (a) ; Figure(8.3.7) (b) ; Figure(8.3.8) (c) ;
Figure(8.3.9) (d) ; Figure(8.3.10) (e)

Transverse vertical sections through the Deep Soft Rock. For key see figure(8.3.2).

for rock 'e', figure (8.3.8). The complete lack of lateral equivalents suggests either pronounced syndepositional subsidence or positive topographic expression during accumulation. Rock 'f', figure (8.3.9), thins centrally down the depositional dip but downwards in the opposite direction. There is a notable central mound. Allowing the possibility of lenses mud within sandstone bodies, rock 'g', figure (8.3.10), has a tendency to thin downwards and centrally, as the base climbs towards the South-East.

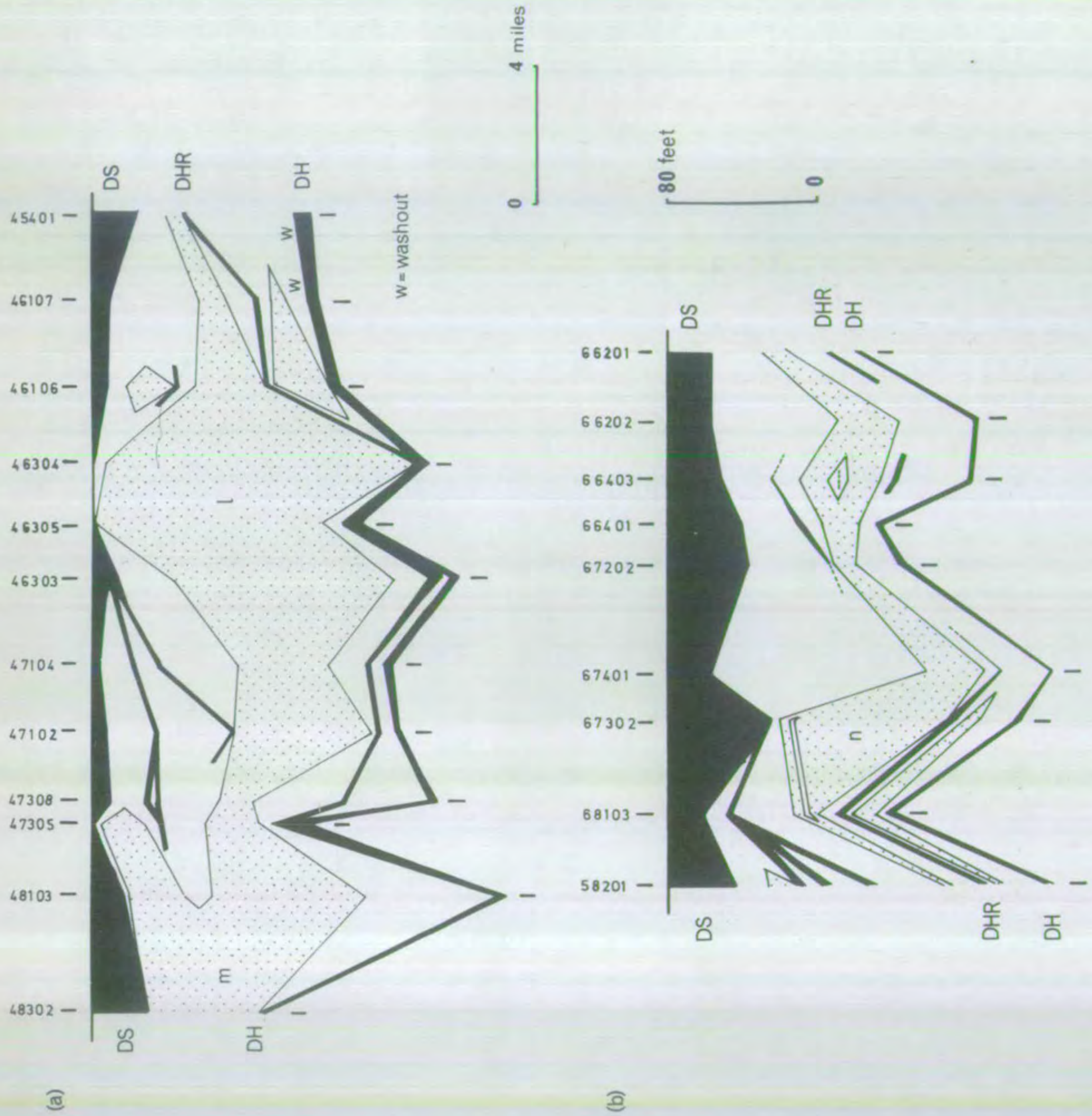
An extensive, down-dip section across a complex of rocks above the Tupton group of seams, figure (8.3.11), was drawn in the South-West of the area where intermediate detail is present. The section is complicated by correlation of interval and sandstone thickness, the ephemeral nature of the Second Piper coal and the possible transgression of cycles by two sandstones. Rock 'h', between the Tupton and Tupton Roof coals, shows definite downwards thinning towards the North-West. Although the base remains close to the combined Cockleshell and Tupton coals, thinning towards the South appears to be accomplished centrally because the Second Piper coal parallels the top of the body. There is a pronounced central mound. Rock 'i', between the Tupton Roof and Second Piper coals, thins downwards down dip but upwards towards the South, with respect to the interval as a whole. However, 'i' terminates abruptly at 45202 and is replaced by rock 'j', at a stratigraphically higher position, in 45203. In this bore log the coal below 'j' is recorded as the 'Second Piper', which is supposed to underlie 'i' as far North as 55103. Thus, unless the coal identifications are faulty, 'i'must climb dramatically from one cycle to another. In this case it thins downwards in both





Figure(8.3.11) (b) ; Figure(8.3.12) (a)

Transverse vertical sections through the Tupton Rock(s).



Figure(8.3.13) (a) ; Figure(8.3.14) (b)

Transverse vertical sections through the Deep Hard Rock. For key see figure(8.3.11).

directions. 'J' thins centrally or downwards down dip but splits into two leaves towards the South. The upper leaf appears to climb southwards from one cycle to another. No reliance can be placed on the downward thinning suggested for rock 'k', in figure (8.3.12), because of the lack of control. The section also shows the abrupt margin of the area of development of a thick sandstone, filling the interval between the Tupton and Parkgate coals.

Two sections were constructed across the Deep Hard Rock. The phase 'l' of the combined bodies, shown in figure (8.3.13), thins downwards both up and down depositional dip, and has a pronounced central mound. 'M' thins by splitting into two leaves southwards; the lower forms a connection with 'l' but the upper overlies the lower leaves of the Deep Soft coal which lie on the flanks of the central mound of 'l'. In part, therefore, 'l' must be older than 'm'. 'N' is an equivalent of 'l'. Downward thinning in both directions, from the central mound, is characteristic, figure (8.3.14).

To summarise, it would appear that upward thinning, taken as diagnostic of an alluvial origin for Carboniferous sandstones in Illinois, is completely absent. Central thinning does occur but its importance is outweighed by frequent downward thinning. Common asymmetry across the palaeostrike is a difficult feature to generate from any alluvial or delta distributary model but is an integral part of a bar hypothesis.

8.3(b) Lateral equivalents

In some cases downward thinning gives rise to extensive sheet-like bodies of sandstone. These are usually equivalent to the lower parts of the central belt, but on the southern flanks they may sometimes be stratigraphically higher. Only one sheet sandstone unconnected with any belt was observed in subsurface. The example lies between the Thorncliffe and Parkgate coals to the North of the area.

The sheet phases in the Westphalian are, therefore, unlike their American counterparts. Formation by overflow of a filled channel, as described by Wanless (1957) or Moore (1960), can be discounted because of the asymmetry.

Hopkins (1958) and Potter (1963) have suggested that the Illinois sheet sandstones were formed during a marine regression. Similar geometry was produced during the Pleistocene regression across the continental shelf in the Gulf of Mexico. Furthermore, bars can be formed during regressions or intermediate still-stands. However, the prograding bars, described by Bernard et al (1962), were formed during a period of net subsidence (Fisher 1968). An additional example described in the Gulf of Mexico by Fisk (1969) was associated with notable asymmetry.

It follows that, in the Coal Measures of central England, bars and sheets could be genetically linked in a system compatible with the evidence from the surrounding rocks, of deposition during a period of net regression.

8.3(c) Statistical tests of thinning characteristics

It is difficult to design any statistical test of the nature of thinning which has any geological significance. In the very simple

Source	SS	df	MS	F
between groups	102	1	102	1.2
within groups	6238	72	87	
total	6340	73		

Table(8.3.15) To test the hypothesis that the basal separation of thick sandstones, from the base of the rock body to the underlying coal, is greater than for thin sandstones.

SS Sum of squares
df degrees of freedom
MS Mean square

example of figure (8.3.1), the ratio of the separations (t_2/t_1) would be proportional to the sandstone thickness for downward thinning and inversely proportional for upward. However, asymmetry and the occasional strong correlation between total and sand thickness complicate the issue. Furthermore, to test for proportionality would require data with almost normal distributions. This could only be obtained by screening and the removal of some of the common cases of a thick sandstone resting directly on a coal. The result would, therefore, not be reproducible.

A very simple test can be used, however, to find out whether the basal separation of thin sandstones is any greater than for associated thick sandstones, as would be the case for the American alluvial model. The result of the analysis of variance, shown in table (8.3.15), suggests that there is no significant difference at any level, and that the alluvial model must, therefore, be rejected. This does not imply the acceptance of the alternatives.

8.4 Erosive Emplacement and Washouts

8.4(a) Erosive emplacement

Although the gross geometry suggests that the Coal Measures sandstones of the East Midlands should be thought of in terms of bars, it would be unwise to dismiss the possibility that, like their Illinois analogues, some were emplaced by erosion. However, the case for erosion in the Mississippian and Pennsylvanian is not watertight.

Siever (1957) proposed that valleys originally cut by rivers were later filled with alluvial detritus, to explain the frequent basal and lateral erosion observed by Weller (1930). This conclusion was repeated over a number of years, notably by Potter <u>et al</u> (1958), Friedman (1960), Beerbower (1961), Doty and Hubert (1962) and Wanless (1957, 1963). However, the occurrence of up-filled channels and marine fossils led to the concept of alluvial cut and marine fill. Again a plethora of literature includes Wanless (1957), Hopkins (1958) and Kosanke <u>et al</u> (1960). However, whether 'marine' is taken literally or, as in Siever (1957), to imply merely a subaqueous environment, it is necessary to postulate a <u>double transgression</u> for each cycle, from coal to marine shale or limestone and from channel cut to fill. It would almost be litotic to say such a hypothesis is unlikely.

To sidestep this problem, marine cut and fill can be proposed (Rusnak 1957). The advantage of this hypothesis is that it does not require tectonic uplift (Wanless 1963) and would not produce a horizon of subaerial weathering and erosion in the surrounding sediments (Beerbower 1961) or in the base of the channel (Swann 1963). No records of weathered horizons have ever come to the notice of the author.

Therefore, even if erosive emplacement could be demonstrated in the East Midlands it would not necessarily imply an alluvial origin.

On the other hand, Kosanke <u>et al</u> (1960) considered that the frequency of channelling was low and that evidence of an unconformable base is present in less than one in five instances. Swann (1964) also considered that the importance of erosion had been overemphasised. The strongest evidence against erosive emplacement is the common observation of a thick sandstone resting on a coal. Weller's (1930) prejudged argument of increased resistance to erosion is not true in fact, nor from the inference of numerous small washouts in coal seams.

Stratigraphic evidence from the East Midlands suggests that the equivalence of a sandstone body to many cycles does not arise from erosion but from lateral interfingering and degeneration of coals. In addition, where a sandstone body consists of many phases, none cut across the associated interval boundaries, section (4). Five independent lines of evidence suggest that erosive emplacement must be rejected.

1) Where they are thickest, sandstones commonly rest on coals without ubiquitous signs of erosion.

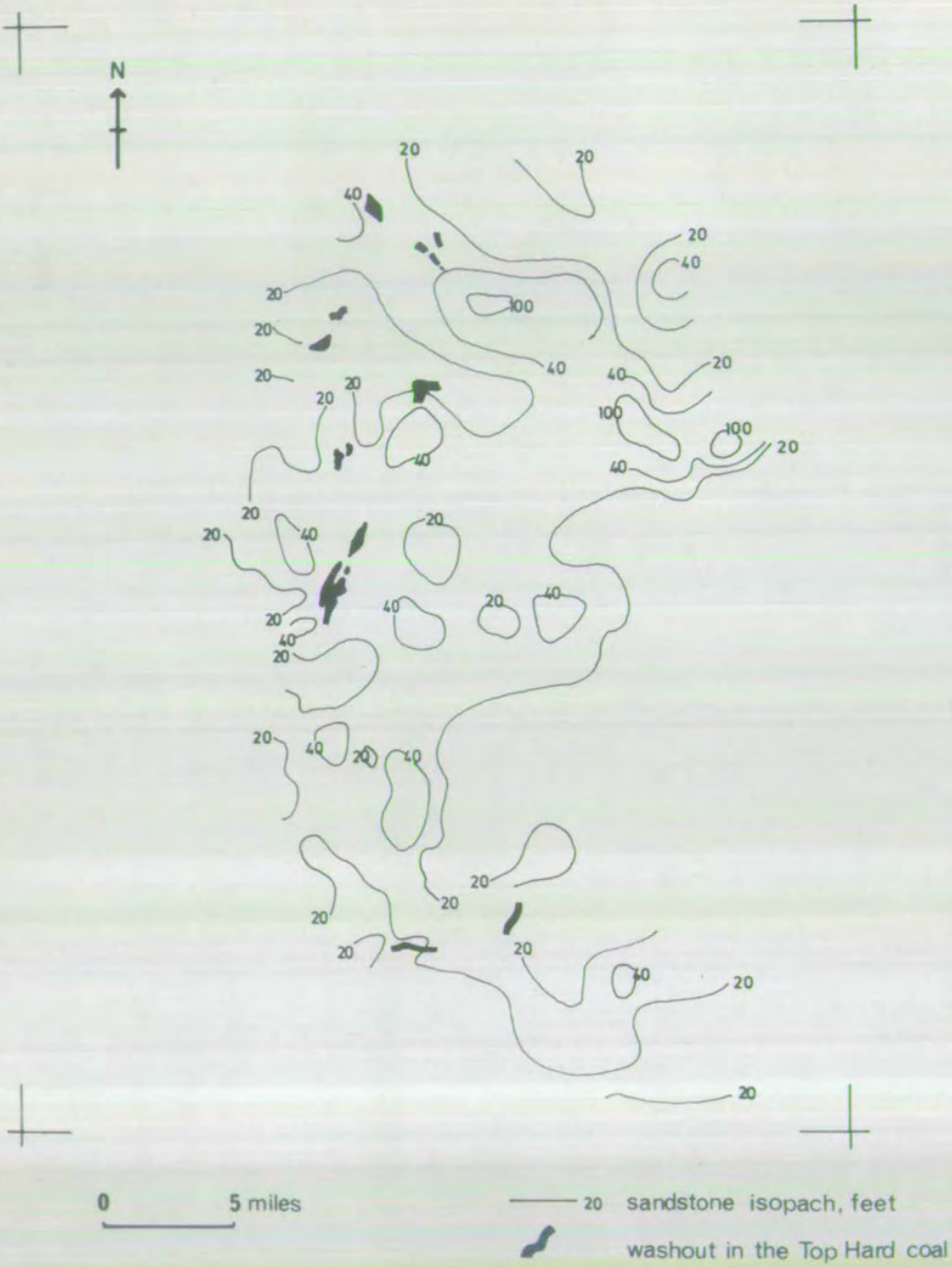
2) Thin sandstones, of laterally equivalent cycles, tend to thicken towards a main body suggesting that they are genetically linked, section (4).

3) There is asymmetry of peat thickness and number of cycles about the axes of maximum thickness of the sandstone belts, section (4).

4) The intervals tend to be thicker where there is a major sandstone, even allowing for the effects of compaction, section (7).

5) Many recent borehole records describe moderately thick sandstones with bases transitional over many feet.

Laterally interfingering, alluvially deposited sandstones have been described by Schlee and Moench (1960) and Flores (1967), and Clarke's (1963) model, although probably dynamically unsound, would not require extensive erosion if the Coal Measure sands were deposited by misfit streams. Delta distributaries are emplaced by compaction and lateral flowage, but may contain evidence of extensive erosion of the channel into its own mouth bar deposits (Fisk 1955, 1961). The preservation of fine detail in coal seams underlying thick sandstones denies the possibility of flowage. Non-erosional emplacement is characteristic



Figure(8.4.1) Isopachs of the Top Hard (Barnsley) Rock.

of all bar or tidal ridge models, and delta-front sands.

Evidence for erosion at the base of a sandstone may, therefore, be decisive with respect to the origin even though total erosive emplacement has been disproved.

8.4(b) Washouts

Coal Measures sandstones are often associated with washouts in the underlying coals. Jones (1938) made a detailed study of washouts in the Wigan area, and concluded that they are at least separated in time, and probably genetically different, from the overlying thick sandstones. As recorded by Edwards (1935) and Jones (1955), and as seen for the Deep Hard to Deep Soft and Barnsley to Barnsley Rider intervals, figure (4.5.3) and (8.4.1), washouts are commonly displaced from the main sandstone belt, although adjacent and parallel. On the evidence submitted, it is difficult to fault Jones' (1938) conclusion that washouts are formed by small streams flowing through the peat swamp. The sandstone ribbons upon and within the High Hazles coal seam (Elliott 1969, fig.3) also are reminiscent of small streams. These ribbons average one mile in width. It seems probable, therefore, that washouts are the first cousins of swilleys, described by Elliott (1965) as river courses established and abandoned within the period of accumulation of the coal seam. There appears to be a whole range of intermediates between these two end members.

If washouts are not formed by the same processes as the sandstone bodies, it seems very coincidental that they should have the same trend. Parallelism would be expected in an alluvial hypothesis. The frequent occurrence on the up-palaeoslope flank of the bodies suggests that the phenomenon can also be explained in terms of a bar model for the sandstones. Brouwer (1953) and Allen (1965) both describe the deflections of small streams along the backs of cherniers for considerable distances before an outlet to the sea is reached. An offshore, or barrier, bar could exert the same influence on an ebb tide. Delta-front sands are intimately associated with small distributaries and presumably the same mechanism can be applied.

In conclusion, it appears that it is difficult to prove that the sandstone bodies are associated with any erosional phenomena, and, therefore, models employing non-erosional emplacement, delta-distributaries and bars, are favoured.

8.4(c) Non-erosive emplacement

The conclusion of the previous section was that the mechanism of emplacement of sandstone bodies by erosion is untenable. Sections across various sandstones, for example figures (8.3.6) and (8.3.13), show that differential compaction plays only a minor role, leaving the alternatives of syndepositional subsidence or that during accumulation the bodies had positive topographical relief. These conclusions follow from the observation that, allowing for compaction, the sandstones are appreciably thicker than their lateral equivalents.

The evidence for the existence of relief is given in section

(8.5). However, it is difficult to apportion the effects of topography and subsidence. In figure (8.3.13) the relief might be estimated from the differences in equilibrium thickness of the Deep Soft 'Peat', which appears to have grown around and finally engulfed the central mound. However, the thinning of the Roof Soft peat over the Deep Soft Rock, in figure (8.3.6), was possibly caused by increased subsidence underneath the buried sandstones. Furthermore, it has been suggested that peat thinning over a thick sandstone is evidence of co-deposition (Friedman 1960).

Evidence from a study of the cross sections of the sandstone belts, and from the comparison of the patterns of sandstone isopachs, figures (4.2.2) to (4.8.3), with the patterns of local subsidence (refer to thickness trend of trend deviations, figure (6.3.8), and raw thickness deviations, figures (6.3.2b) to (6.3.8b), because of the very strong correlation between thickness and subsidence) shows that the sandstone bodies coincide with zones of excess local subsidence. It is unlikely that downwarping on the local scale could produce the complex features of the sandstone bodies that have been discussed above (e.g. repeated parallelism) or are mentioned later (e.g. grouping and offset). If a causal relationship does exist, it, therefore, appears that it is more likely that subsidence is triggered-off by localised sand deposition.

This theory is unattractive, since it requires the assumption of many unknowns, and possibly a very fine geophysical balance. However, there is some evidence of such a process in modern depositional sites. McFarlan (1961) found a two-component system of subsidence in the Mississippi area, showing increases down depositional dip and towards the centre of the alluvial trench. Subsidence is, therefore, influenced by loading by sedimentation. Fisher and McGowen (1969) stated that in a relatively unstable basin subsidence is generally a response to a sediment load. Fisk (1960) invoked subsidence, arising from compaction and downwarping, to give rise to the accumulation of abnormally thick sedimentary facies.

Williamson (1967) postulated differential subsidence to emplace sandstones associated with local coal splits. Schlee and Moench (1961), for the Jackpile alluvial sandstone, and Jones (1955), for the Westphalian sandstones in Northumberland, both suggested that the necessary downwarping was part of an overall tectonic pattern, in space and time respectively. However, in the East Midlands the downwarps cannot be related to pre-Permian structural elements since they have orthogonal trends; section (6.7).

8.4(d) The relation of sandstones to coal splits

The problem of the origin of coal splits and their relationship to sandstones, which may fill them to the exclusion of all other sediments, is related to the enigmatic cause and effect argument about subsidence and sedimentation. A split, of at least moderate areal extent, can arise in two ways. In the first case, depressions formed by local subsidence are progressively filled with sediment. Peat growth is continuous away from the unstable area. In the second, sediment is localised by depositional processes and emplaced by subsidence. Some areas receive little or no sediment. If the process is subaerial, peat growth could be continuous close to the line of split, but if subaqueous cessation of growth should occur locally, although at large distances it could continue.

Elliot (1969) has suggested that both possible equivalents of sediments in the split, a thickness of coal or an extensive dirt or high sulphur band , can occur. The former is more difficult to prove. Submergence and localised accumulation is, therefore, a possible mechanism in addition to subaerial deposition.

Where splits in major seams occur close to belts of thick sandstone the geography becomes a decisive factor. The simplest example of a distally thickening sequence across a sand belt is given by the Deep Soft Rock and the Deep Soft and Roof Soft coal split; figures (4.6.4) and (4.7.1). However, coals may also combine distally across major sand belts, as shown by the Roof Soft Rock and the Sitwell split into Top and Roof Soft coals, and the Tupton Rock 'h' and the Tupton and Tupton Roof coal split, figures (4.7.3) and (4.7.1), and (4.3.4).

The asymmetry suggests that alluvial or deltaic models must be rejected. Both types of split could be explained if the sandstones were originally bars associated with distal thickening (Krumbein and Sloss 1963) or proximal thickening (Fisk 1959).

8.5 Grouping, Inheritance and Offset

The cause of the relationships between the belts of sandstone is an important guide to their origin. The effects of compaction are very important and many pieces of evidence apparently taken for granted in the following discussion are treated in detail in section (7).

Referring to the East Midlands coalfield, Elliott (1968) noted what he called an 'inheritance phenomenon' or a tendency for 'shoestrings' to be located in the same general area, throughout the deposition of a continuous sequence of cyclothems. Similarly, Berryhill (1967) recorded the 'stationary' positioning of channels for six or more cyclothems in the upper Pennsylvanian and lower Permian of the Appalachian Basin. Antithetically, Mueller and Wanless (1957) described offset between successive sandstones in the Pennsylvanian of Illinois. Offset in the middle Allegheny Group of Eastern Ohio is shown in figure (9) of Flores (1967).

Offset is common in the East Midlands, and confirmed examples for elongate sandstones are listed in table (8.5.1).

A certain amount of confused terminology exists in the literature and it is clearly possible for offset and inheritance to be coincident (see for example Brown et al 1967). However, grouping, and offset within groups, raise problems which must be considered separately before any synthesis can be attempted.

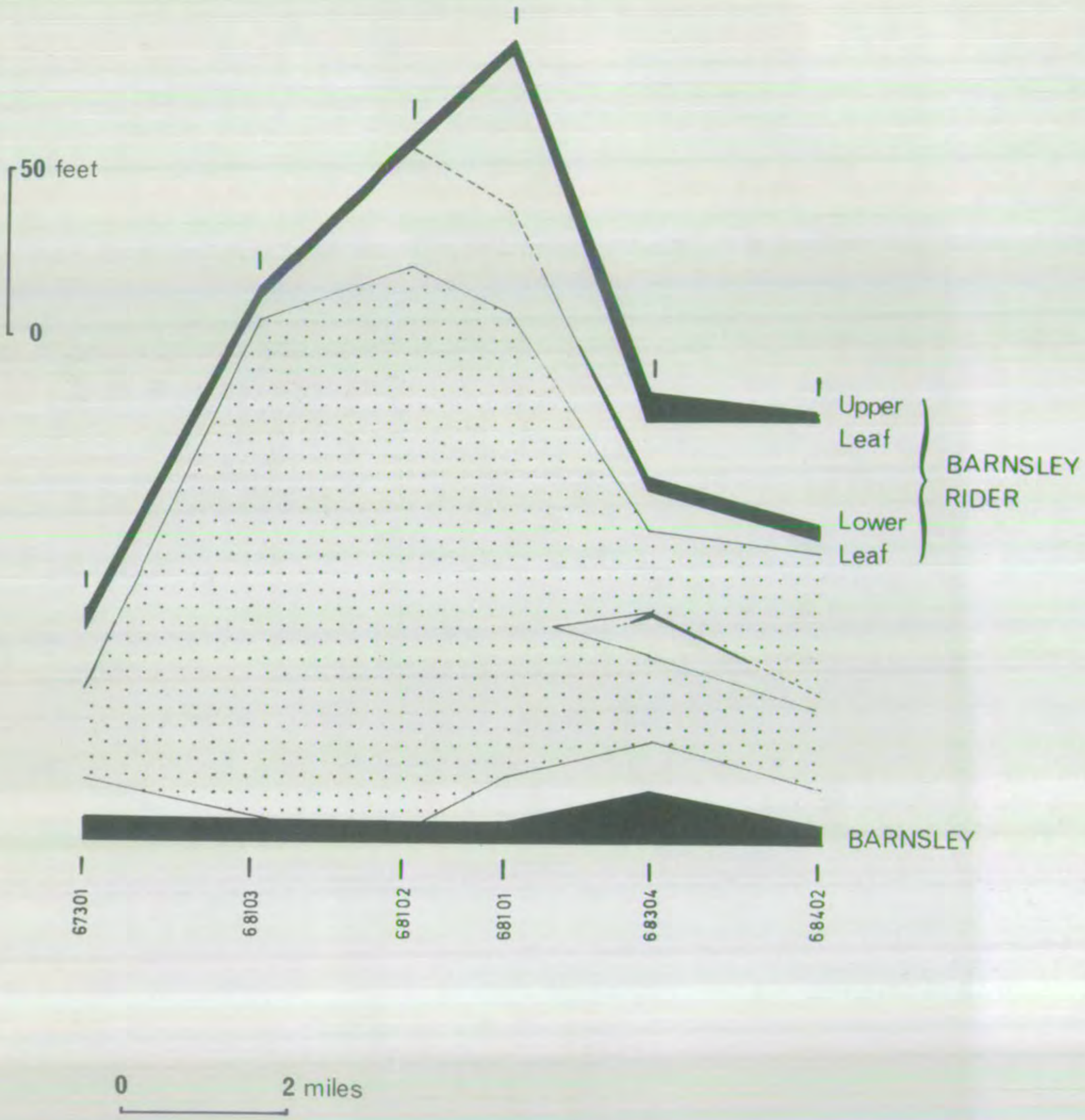
Since the sandstone belts avoid the locus of maximum subsidence, near Manchester in figure (3.0.2), it is unlikely that grouping is controlle by regional downwarping. It has already been demonstrated in section (8.4c) that it is also improbable that local subsidence could control the location of the sandstone bodies and, therefore, this mechanism cannot be employed to explain grouping and offset. Localisation of sand accumulation through the operation of normal depositional processes is the least unlikely hypothesis.

Of the three basic models which could produce elongate sandstones, alluvial and distributary mechanisms are unlikely to produce repeated parallelism across the palaeostrike unless under strong tectonic influence (Brown et al 1967). On the other hand sand belts are most likely to be

Table(8.5.1) Occurrences of offset between sandstone belts in the East Midlands Coalfield.

lower sandstone body	upper sandstone body	offset in relation to depositional dip
a) subintervals		
Deep Hard 'p'	Deep Hard 'l'	down
Tupton 'k'	Tupton main belt	up
Tupton 'h'	Tupton 'i'	down
Tupton 'i'	Tupton 'j'	down
b) intervals		
Deep Soft 'c' to 'd'	Roof Soft 'a' and 'b'	up
Parkgate main belt	Deep Hard 'm' and 'l'	up
Tupton 'k' and main belt	Parkgate main belt	down

Table(8.5.1)



Figure(8.5.2) Transverse vertical section through the Top Hard (Barnsley) Rock, to show the split in the Barnsley Rider over the axis of maximum thickness. For key see figure(8.3.11).

grouped if they are formed at hinge lines, since these will remain approximately in the same place for the same pattern of subsidence. An example of this characteristic was given by Fisher and McGowon (1969) from the Eocene of Texas. Krumbein and Sloss (1963) stated that hinge line sands can be preserved during regression, a concept which is compatible with the evidence from the surrounding rocks in the Coal Measures.

Unfortunately it is not possible to find evidence of hinge lines because intervals with sandstones are so deformed by syndepositional subsidence and differential compaction that any evidence is obscured, and intervals without sandstones could not be expected to show hinge lines.

There is a general concensus of opinion that offset within groups is caused by the topographic expression of the lower body during deposition of the upper. This expression can be independently proved in the Coal Measures by the occurrence of splits in the Barnsley Rider Coal across the Top Hard Rock, figure (8.5.2), and in the Deep Soft Coal across the Deep Hard Rock, figure (8.3.13). Elliot (1968) found that brown seatearths occurred towards the margins of the basin and over thick belts of the Tupton Rock. He concluded that the belts may have been "slight palaeotopographic highs." The frequent loss of the lower leaves of a coal over a thick sandstone may be taken as evidence for topographic expression; although, on the large scale, peat thickness tends to be related to subsidence, section (7), the sandstone belts are themselves emplaced by subsidence. Thus the coals thin where they should thicken. Accepting this argument suggests that subsidence is caused by depositional loading under the sand belts, since the reverse should give rise to topographic depressions. However, as discussed below, the thinning of the coals may have been amplified by compaction. Friedman (1960) has proposed co-deposition of alluvial sand with peat to explain a similar phenomenon, but his model cannot be applied in the case of the Deep Soft Rock 'c' and the Roof Soft coal, figure (8.3.6), which are separated by shales.

Topographic irregularities, found necessary to explain offset between American channel-sand bodies, are supposed to arise by differential compaction (Edmunds 1968). The irregularities must, therefore, be developed at the top of one cyclothem before the onset of deposition of the sediments of its successor. However, unless the consolidation rate is very much less than the sedimentation rate, the sediment pile will accumulate approximately at compactional equilibrium, and any posthumous adjustments will be soaked up during the long time involved in peat formation, section (7). Adjustments of this kind will tend to give greater thickness of peat over zones where the underlying sediments are less sandy. Since the percentage of sand is distributed evenly across the study area this mechanism could not give rise to the apparent relationship between peat thickness and basinwide downwarping.

The topographic irregularity of the new depositional surface will, therefore, be minimal and the inheritance must be passed on in some other way. The most likely mechanism appears to be the compaction of peat. Initially peat is very unstable so that it compacts proportionally to its own thickness as well as the overburden, section (7.3d). The buried topographic highs will, therefore, be exhumed because they are overlain by reduced thicknesses of peat, if an evenly distributed overburden is applied over the whole area.

However, location control by topographic influences, as described by Sabins (1963), is not a simple process. He found it necessary to assume not only that the top of the interval is a time marker and that subsidence and accumulation rates were almost constant, but also that differential compaction had not distorted these late Cretaceous rocks. Fortunately, such an unlikely hypothesis is not required to explain offset between bars, because a bar with relict topographic expression would tend to accentuate shoaling and thus give rise to wave diffraction and the deposition of new sediment.

Since the same basinwide subsidence pattern was in operation during the whole of the Westphalian, section (3), it seems probable that successive bodies of delta-front sand would be deposited in the same general area. However, there appears to be no simple way to produce the complex offset, of some of the Coal Measures sandstones, if this model is proposed.

In conclusion, grouping and offset appear to be an acceptable part of development of barrier and offshore bars through time. On the other hand, while there is no reason that alluvial, bar finger or delta-front sands could not exhibit such features, it is necessary to postulate some complex, external control. According to the principal of Occam's Razor the bar model is more acceptable.

A quote from Fisher et al (1969) is a relevant means of concluding this section: "First, in a relatively unstable basin, where subsidence is generally a response to sediment load,..................., sites of deposition of particular facies tend to be maintained. Thus the barrier bar system, for example, can be constructed of several individual barrier bars, the main features of which are similar to those of the larger system."

8.6 Sedimentary Structures.

Thirteen major sandstones were examined at outcrop. Ranging in age from lower Communis to upper Lower Similis Pulchra they were the Kilburn, Mickley, Tupton, Deep Hard, Clay Cross Soft, Second Ell, First Ell, Second Waterloo, Dunsil, Top Hard, High Hazles, Main Bright and Clowne rocks. By convention the names refer to the underlying coal or groups of coals.

The exposure, afforded mainly by quarries, is poor, scarce and rarely three dimensional. Readings of orientations of structures were limited by accessibility and the planar nature of quarry walls. For these reasons nested sampling, as described by Potter and Siever (1955), was not attempted and measurements were taken on a common sense basis; for example one reading was taken per accessible coset.

Of the great variety of sedimentary structures that would be expected to occur in elongate sandstones, only repeated festoon bedding, the 'Nu' cross-stratification of Allen (1963), was conspicuous in its absence. Isolated festoon-like structures were recorded but in many cases appear to be vertically filled erosional channels.

The other most striking feature was the great lateral extent of cosets when compared to their thickness. This was observed for thick, medium and thin bedding, where the terms refer to 5 and 20 cm. limits defined by Coleman <u>et al</u> (1964).

The great majority of cross-strata were found to be concave upwards, tapering downwards into thinner toesets and bottom-sets.

Measurements of the maximum inclination to the coset margin never exceeded 35° and most were between 10° and 20°. Planar cross-strata were usually inclined at the smallest angles. High angle planar types were not seen. The few convex upwards cross-strata recorded could generally be shown to have been affected by slumping. Cosets were variable in thickness. The maximum thickness recorded in the field was about 4 feet, but Elliot (1968) has found examples of 6 feet.

The term 'flag' or 'flagstone', which refers to a bedding unit between 1 and 10 cm. in thickness, was found valuable in field descriptions. Where flagstones occur as cross-strata they can be laminated parallel to their margins, although they are usually homogeneous and sometimes cross laminated in the opposite sense to their own discordance.

Localised current activity was attested to by the occurrence of wide and shallow washouts. A typical example from the Tupton Rock was 12.5 feet wide and only 1.25 feet deep. The greatest depth to width ratio was 1:6. The washouts were either up, down or vertically filled, or side filled where the successive bed consisted of cross-strata. Veneers were often found to blanket the channel margin, suggesting a separation in time of the cut and fill episodes.

Flat bedding was found to be the most common sedimentary structure. The bedding occurred on all scales but flat laminated or homogeneous flags were common. Very thick bedded, homogeneous sandstone was frequently observed possibly because it yields the best building stone; although usually completely featureless, isolated climbing ripples were sometimes observed. The margins of these homogeneous sandstone beds are usually irregular. The most plausible field explanation was the occurrence of small banks of sand, generally less than one foot high.

Surfaces showing ripples were rare because of the nature of the outcrop. Poorly preserved examples of symmetric and asymmetric forms were observed. Amplitudes of less than one centimetre were recorded with wavelengths of the order of six centimetres.

The upward sequence of structures shown in the longest exposures in quarries, are partly the result of the aim of the excavation. Furthermore, the usual upward transition from massive to medium and thin flat bedding is in part accomplished by unloading. Flagstones produced in this way are always homogeneous with irregular margins. Therefore, in many cases the upward transition to true flat bedding and lamination could be proved. In no case could the exact position of the transition, with respect to the whole rock, be proved.

Incomplete sections of the Tupton and Top hard Rocks were constructed from isolated exposures using the detailed stratigraphy. The possibility of lateral transitions between outcrops could not be allowed for. Composite sections are recorded in tables (8.6.1) and (8.6.2). The association of cross-stratifications were flat bedding, on the medium, thin and lamination scale, and its non-appearance with massive sandstone, except in the form of isolated ripples, suggests that the general sequence can be summarised as in table (8.6.3). The basal unit is least persistent and often absent where the body is thickest.

Flaser bedding and rib and furrow structures observed in cores, were not seen at outcrop. Conglomerates and breccias, composed mainly of ironstone, shale, siltstone and coal fragments, commonly occur in the lower portions of thick sandstones. They are not ubiquitously basal and can occur in common but discrete horizons throughout the lowest tens of feet.

Table(8.6.1) Composite vertical section through the Tupton Rock.

locality	thickness,feet	grain size	internal structures
gap	?		
0/36203/-	3	fn	tn ; c l and c f
gap	?		
0/36202/-	8	fn	tn ; c l and x l, one ch
gap	?		
0/36201/-	4	fn	tn ; c l and x l, one ch, some small ch's (side filled)
gap	?		
0/35403/-	20	fn, some fm	tn ; mainly x l, some c l
	8	fn	th, h ; some tn x l partings
gap	?		
0/35402/-	13	fn, some fm	th, h ; rare c l partings one down filled ch
	5	fm	tn ; x l
	3	fn	md ; h
gap	?		

Table(8.6.1) tn,md,th = thin, medium, thick bedded ; c = conformable
x = cross stratified ; l = laminated ; f = flaggy
h = homogeneous ; ch = channel ; fn,fm = fine & fine medium

Table(8.6.2) Composite vertical section through the Top Hard Rock.

locality	thickness,feet	grain size	internal structures
gap	?		
0/46207/-	2	fn (silty)	tn ; c l, mainly x l, some ripple drift
gap	?		
0/46204/-	5	fn	tn ; c l
	9	fn	tn ; c l, some x l, few small ch's
	8	fn	th ; h
	0.2	shale	c l
	10	fn	th ; h
gap	?		
0/46210/-	6	fn	th ; h, some irregular f
gap	?4		
0/46209/-	5	fn	md ; cl , rare asymmetric ripples
gap	?1		
Top Hard coal			

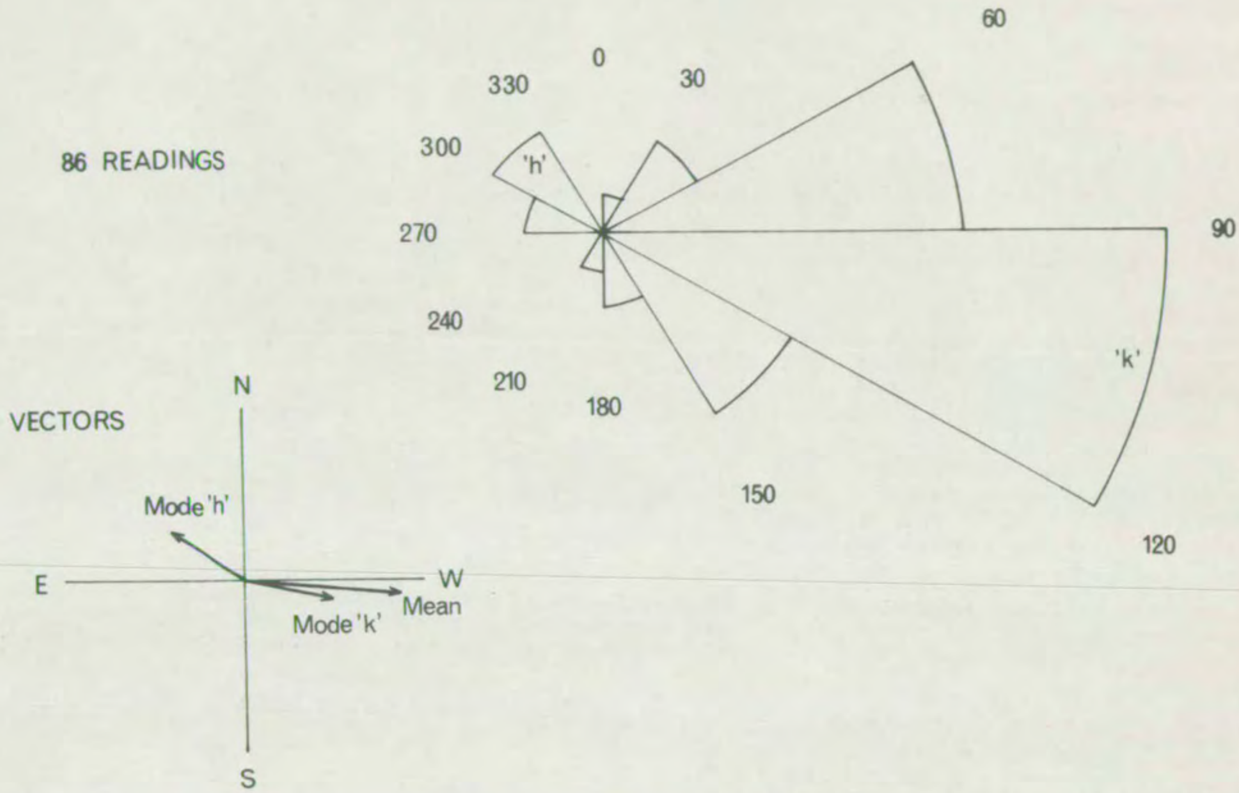
Table(8.6.2) for explanation of symbols see figure(8.6.1)

i) Conformable thin and sometimes medium bedding units ; common conformable lamination ; less common cross-stratification which is nearly always on the lamination rather than flaggy scale.

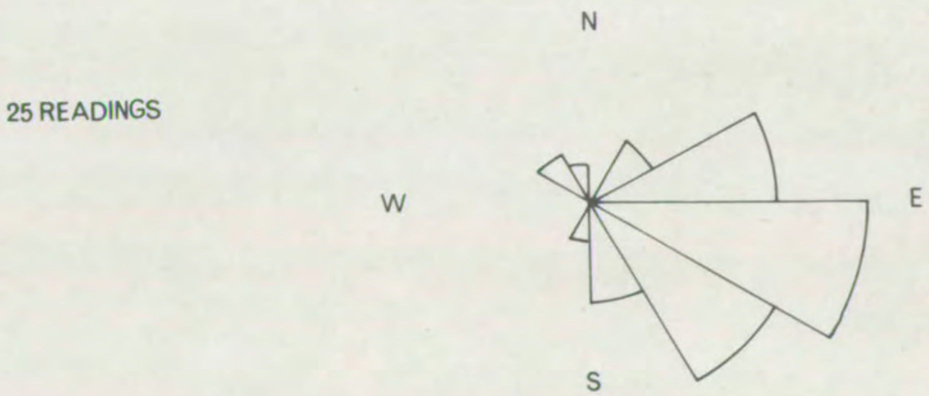
ii) Thick bedded and occasionally thin or medium bedded ; bedding units often have irregular margins ; sandstone usually homogeneous but laminations in partings occur, and may be conformable or cross-stratified; partings usually thin or medium bedded.

iii) Thin bedded ; conformable laminations ; some ripples; rare washouts.

Table(8.6.3) Generalised vertical sequence of sedimentary structures in the sandstones of the East Midlands Coalfield.



Figure(8.6.4)



Figure(8.9.2)

Measurements of orientations of sedimentary structures were converted into palaeocurrent directions using the usual criteria. Structural errors were eliminated by unrolling about the strike; the procedure is acceptable where the initial dips are small (Ramsay 1961). The results were plotted in a single rose diagram, figure (8.6.4), because, with unknown sources of variance, there is no a priori criterion for separation. The diagram shows a strong mode towards the East- South-East, and a small secondary mode towards the North-West, which in part may arise from misinterpretation of ambiguous structures. Currents flowing towards the South-West quadrant were very rare.

Organic remains and structures in the sandstones are restricted to plant fragments, roots and burrows. Plant fragments occur throughout the sandstone bodies but the larger fragments tend to be restricted to the bases of washouts. In the thicker sandstones roots and burrows are restricted to the top ten feet, but can occur throughout the thinner sandstones which also contain mudstone lenses with freshwater mussels.

Environmental inferences can be drawn from comparison of sedimentary structures in the Westphalian sandstones with Recent sands, and their orientations with the palaeogeography. To a limited extent the hydrodynamic environment may be discussed empirically.

8.7 Hydrodynamic Interpretation

Although advances have been made in recent years in the field of applied hydrodynamics (Simons et al 1962, Middleton 1965, Bagnold 1966,1968) a detailed reconstruction of the palaeoflow regime, as in Jopling (1966), cannot be attempted without a fairly detailed knowledge of the depositional environment; such a prerequisite is the object of the present study.

For practical purposes, however, the depositional environments of the categories under discussion have sufficiently similar hydrodynamic features to warrant some empirical investigation.

Cross-stratification of the type found in the Coal Measures was probably formed by the migration of sand waves (Potter et al 1963). A comparison of the mechanisms of production of foresets by migrating sand waves (Brush 1958) and delta advance (Jopling 1963, 1965), shows such a great similarity that Jopling's (1965) comments may be applied to this analysis.

Jopling (1965) showed that tapering, concave-up foresets, typical in the Coal Measures, indicate relatively lower flow depths, and/or higher velocity, and/or smaller mean grain size, the net effect being to increase the amount of sediment in suspension compared to bedload. The strong positive skewness in the grain size distributions of the Coal Measures sandstones, section (8.11), is partly diagenetic and partly original, so that volume for volume much sediment could have been in suspension at low velocities and appreciable depths. It is, therefore, not necessary to postulate low flow depths and high velocities, which are more common in alluvial than deltaic or 'marine' environments.

The abundant flat lamination can be produced in the upper part of the upper flow regime under plane bed conditions (Simons et al 1962), but can also be formed in the lower flow regime by the movement of ripples down a depositional surface (McKee 1939, Jopling 1966). In the Coal Measures' sandstones, the occurrence of small broken plant fragments in cross-stratified deposits and larger, delicate fragments in contiguous horizontally laminated deposits, suggests but does not prove that the lower flow regime is the more likely hypothesis.

8.8 Comparison with Recent Sediments

The sedimentary structures described in section (8.6) can be compared with those being formed today in the range of environments specified in section (8.0). These categories are not equally represented in the literature because they are not equally accessible. River sands are easily studied and the literature is voluminous but equipment suitable to obtain undisturbed cores from unconsolidated marine sands has only recently been developed.

It should be noted that the unmentioned assumption of the principle of unifomitarianism may not be justifiable when comparing modern and ancient sands, because of the evolution of vegetation, which is one of the most effective process agents operating in modern depositional environments (Schumm 1968).

8.8 (a) Cross-stratification

Although all the examples of cross-stratification seen in the Coal Measures sandstones could have been formed by alluvial processes, there is a marked difference in frequency of occurrence. A summary of the characteristics of modern alluvial sediments, taken from Allen (1964), is presented in figure (8.8.1). Douglas (1962) and Harms et al (1962) suggested that festoon bedding is the most common feature, unlike the Coal Measures where planar cosets are in the majority. Allen (1964, 1965) and Potter and Pettijohn (1963) have described planar cosets with concave-up foresets from alluvial sands. Low angle planar foresets have been attributed by McKee (1939) to the 'crevasse-splay' subfacies, but Allen (1965) has suggested that they might be discordant numbers of the flat bedded subfacies.

SUMMARY OF CHARACTERISTICS OF MODERN ALLUVIAL SEDIMENTS[1]

CHARACTERS	DEPOSIT	CHANNEL LAG	LATERAL ACCRETION	CREVASSE SPLAY	CHANNEL-FILL	VERTICAL ACCRETION		
						LEVEE	BACKSWAMP	UNDIVIDED
ORGANISMS	Freshwater molluscs, ostracods, worms.				x	x	x	x
	Authochthonous roots and rootlets.				x	x	x	x
	Drifted twigs and leaves.		x	x	xR	x	x	x
	Drifted branches and trunks.		x	x	xR	xR		xR
GRAIN SIZE	Clay				x	x	x	x
	Silt		xR	x	x	x	x	x
	Very fine sand		x	x	x	x		x
	Fine sand		x	x	xR	xR		xR
	Medium sand		x	xR	xR	xR		xR
	Coarse to very coarse sand		x		xR			
	Gravel to gravelly sand	x	x		xR			
SEDIMENTATION STRUCTURES	Suncracks				x	x	x	x
	Lamination[2]				x	x	x	x
	Ripple-bedding and/or small scale assymmetrical ripples.		xR	x	x	x		x
	Large scale cross-stratification and/or large-scale asymmetrical ripples.		x		xR			
	Flat-bedding[3]		x	x		x		x
	Irregular layers[4]	x	x					
	Erosional surfaces between sedimentation units.	x	x			x		x
GROSS BEDDING[5]	Uniform fine deposit				x	x	x	x
	Layered coarse and fine deposit.		xR	x	x	x	xR	x
	Uniform coarse deposit	x	x					
GEOMETRY		Elongate lens	Thick sinuous elongate prism	Flat lens	Thick narrow curved prism	Thin ribbon-like sheet	Sheet or lens	Sheet or lens
SEQUENCE[6]		In almost all modern floodplains, the vertical sequence is from coarse sediments resting on an erosion surface upward into fine deposits.						

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Table(8.8.1) A summary of the characteristics of modern alluvial sediments ; from Allen(1964).

Cosets formed in alluvial environments range from a few centimetres to over one metre in thickness, encompassing most, but not the largest, examples from the Coal Measures.

Experimental work in offshore bars, by McKee and Sterrett (1961) has shown that cross-strata of moderate discordance (16° to 20°) can be concave-down or planar and concave-up, depending on whether sediment is withheld or fed to the seaward side. The planar foresets have a slight discordance and dip in to opposite directions from the other types. Planar foresets with high discordance, not recorded in the Westphalian, are formed in shallow water. Bigarella (1965) has recorded these features in Brazilian bars, together with trough cross-stratification. Masters (1967) has shown how this type of bedding can be formed offshore by rip-currents. Its absence in the Coal Measures sandstones could be a function of grain size. Occasional festoons in tidal bars have been recorded by Ball (1967).

Cosets in bars can be formed during storms, in which case they can be medium or large scale, or by reworking by everyday currents, when they are usually thin (Ball 1967).

Very little is known of the cross-stratifications in tidal ridges. Houbolt's (1968) cores (Hbo 155^{1}, 156 and $158^{\overline{\underline{II}}}$) suggests planar foresets with a discordance of about 20°.

The three deltaic subenvironments associated with elongate sand bodies, channel, levee and mouth bar, show all but three of the sedimentary structures in a prograding distributary, listed by Coleman <u>et al</u> (1964); figure (8.8.2). These are, lenticular lamination, shell fragments and flaser structures. The last named is common in the East Midlands' sandstones. The simple and planar cross-stratification, recorded as "common" or "abundant" in the three subenvironments, was not seen in the Coal Measures' sandstones.

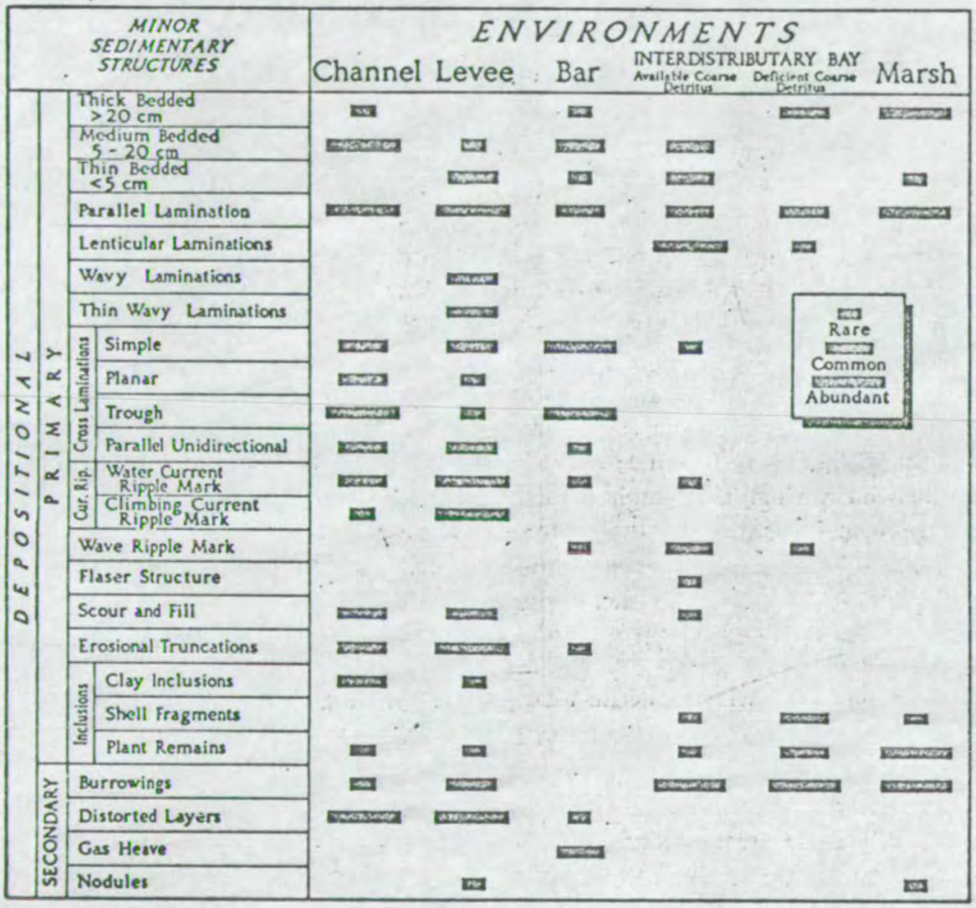


Fig.5. Occurrence of sedimentary structures in depositional environments. Tabulated from cores taken in Garden Island Bay study area.

Figure(8.8.2) A summary of the characteristics of modern of modern delta distributary sediments ; from Coleman et al (1964).

Bedding in the Mississippi Delta is usually medium or thin, and Fisk (1960) has suggested upper limits of nine inches, for parallel unidirectional sets, and two inches, for trough cross-sets.

8.8.(b) Flat bedding

The almost ubiquitous occurrence of flat bedding in shallow water sands, makes it the least important structure for discriminating between depositional environments.

Allen (1964) found that flat bedding was recorded from all alluvial subenvironments except back-swamp, channel lag and channel fill. However, he clearly disagrees with his own literature analysis by describing flat bedded channel fills in the Devonian. Flat bedding is quite common but not abundant in deposits of braided rivers (Douglas 1962) and point bars (Harms et al 1963, Bernard and Major 1963).

Common or abundant in all Coleman et al (1964) deltaic sub-environments, flat bedding was confirmed from mouth bars by Fisk (1960).

Bigarella (1965) recorded "normal lamination" in association with trough-cross-stratification in his nearshore bars. However, work by Fisk (1959) and Moore and Scruton (1957) suggests that flat bedding may be the most common feature in bars formed in deeper water.

Flat bedding has already been described as possibly formed by the migration of ripples, and, therefore, any depth indication may not be significant.

8.8 (c) Ripples

Asymmetric current ripples can occur in almost any environment and oscillation ripples have little depth significance, ranging from the littoral zone to six hundred feet or more (Draper 1967).

However, climbing ripples sets, for example the types listed by Jopling and Walker (1968) which are formed under conditions of net deposition, were not seen. Cross lamination, produced by ripple migration, usually occurred in flat cosets indicating reworking of sediment under zero deposition. Cosets of this type were rarely more than a few centimetres thick.

Isolated climbing ripples were recorded in the thick bedded homogeneous sandstones. Growth under net deposition and burial suggest that the accummulation rate may have been high.

8.8 (d) Homogeneous Bedding

Hamblin (1962) has shown that many, apparently featureless sandstones in fact contain sedimentary structures. This may be true for the common homogeneous sandstones in the Coal Measures. However, the occasional, but obvious, occurrence of ripple lamination and the alternation of homogeneous and laminated sandstones suggest that this is not simply a matter of observation.

Modern homogeneous sands have been described by Moore and Scruton (1957). No doubt X-radiography would reveal internal structures but Bouma (1964) has suggested that laminations can usually be seen without resort to this technique.

Therefore, it is possible that homogeneous bedding in sandstones may be the product of a distinct depositional environment, which may be the same as that in which similar sediments are being formed today. However, homogeneity can also be caused by excessive bioturbation in modern sediments (Ball 1967). The Carboniferous sandstones commonly contain burrows in their upper parts only, whereas homogeneous bedding tends to occur in the lower parts. The occasional perfect preservation of ripple lamination also suggests that bioturbation is not a possible mechanism.

Homogeneous, or at least non-laminated, sands are being formed today in a limited range of environments. Moore and Scruton (1957) reported homogeneous bedding in coarser sands in a back-bar environment, and in finer sands on the seaward side of barrier islands. At depths of 90 feet the homogeneity was found to give way to lamination and may, therefore, be formed by strong wave action (van Straaten 1959). Bernard and Major (1963) described "poor" bedding in alluvial levee deposits. "Massive" bedding in deltaic levees has been reported by Fisk (1960), who inferred that "massive" implied homogeneity by stating that "as the levees increase in size they reflect seasonal deposition and exhibit well defined bedding."

Collinson (1968) has suggested that homogeneous bedding is formed in the upper part of the upper flow regime but there is no independent evidence to suggest strong current activity during the deposition of the Coal Measures' sediments.

If homogeneity can be taken as an indicator of depositional environment, levees in river or delta systems or the seaward flanks of barrier or offshore (?) bars are the most probable depositional sites.

8.8 (e) Bed thickness

Bedding in alluvial sediments is usually thin and medium but is occasionally thick. McKee (1939) has recorded a thickness of 40 inches from a bed of sand in the "delta" of the Colorado River. Sand ridges in shallow seas tend to be thick bedded (Ball 1967) near the base but there is a vertical reduction to thin or medium bedding. There are exceptions to this generalisation. For example, Bigarella (1965) found only thin and medium bedding in sand ridges of the Parana coastal plain, and Wermund (1965) found thick and medium bedding in an Eocene neritic bar.

Although bed thickness does not appear to be a significant criterion for the differentiation of alluvial and bar deposits, it can be used to show that a bar finger model is unlikely. Thick bedding, common in the Coal Measures sandstones, was only rarely found in channel fill and mouth bar deposits and never in a levee (Coleman et al 1964). In addition Fisk (1960) has stated that thin bedding is a characteristic of delta sands.

The wide lateral extent of many bedding units, as in the Coal Measures' sandstones, would, on an a priori basis, be expected in delta and bar environments, but not in alluvial flood plains. However, Frazier and Osanik (1961) and Harms et al (1962) have recorded widths of ninety and fifty feet respectively, measured at right angles to the mean stream path. On this basis many, but not all, exposures would not have shown the termination of a bedding unit.

In conclusion, the thick bedding associated with homogeneous sandstone in the Westphalian, was most probably formed in a shallow water bar, but an alluvial origin cannot be excluded.

8.8 (f) Erosional features, conglomerates and breccias.

Small washouts are typical of an alluvial plain and especially of a braided river (Doeglas 1962). However, washouts are not uncommon in bars where they are cut by eddy rip-currents, or in deltas, where they have been recorded in channel fill and levee deposits by Coleman et al (1964). On the other hand Fisk (1960) reported no washouts. Small distributaries produce washouts in delta-front sands.

Conglomerates are an integral part of alluvial sediments. In Allen's (1964) classification they are channel lag deposits formed during lateral stream migration. There are problems involved in the application of this model to Coal Measures' sandstones. Conglomerate horizons are often scattered throughout the lowest twenty feet, and rarely seen to occur at the absolute base of the sandstone. If each horizon marks the passage of the stream bed, then river depths in the order of eighty feet will be required to produce the uppermost conglomerate. It is difficult to reconcile such a large river with the small scale of many of the sedimentary structures.

Abandoned distributaries in the Rhone Delta contain basal lag deposits. Conglomerates have also been reported from offshore bars. Ball (1967) found a penecontemporaneous conglomerate in the Cape Sand in the Bahamas.

8.8 (g) Organic debris

Plant fragments occur throughout the Coal Measures sandstones, although often only as comminuted material. Larger fragments are often concentrated in the bases of washouts, suggesting that they were either associated with the current which cut the channel, or that they collected in the topographic depression before the 'fill' sands were introduced. In the latter case they might have floated in to the environment from an appreciable distance. The occurrence of these fragments does not, therefore, suggest a continental source for the fill sands, as proposed by Siever (1957) and Kosanke _et al_ (1960).

Shelton (1967) has suggested that alluvial sands contain 'wood fragments' as opposed to the 'plant material' in barrier bars. It is difficult to apply this criterion to the Westphalian, because of the problems of preservation, and density of Carboniferous wood.

The complete absence of shelly fauna is striking, but not necessarily significant. Many features of an area of active sand deposition could be adverse to the establishment of a community, and, in addition, the preservation power of a porous sandstone is limited. Swann (1963) reported marine fossils from the base of Chesterian and Genevevian sandstones in Illinois, and a systematic search of their British analogues might produce similar finds. Non-marine bivalves have been recorded from shale beds in sheet sandstones in the East Midlands which are the equivalents of the thick sandstone belts.

8.8 (h) Upward Sequence

The absence of any exact analogue, in recent sediments, of the upward sequence of sedimentary structures in the Coal Measures' sandstones, may reflect error, arising from lateral variation, in the composite sequences.

The best approximation, from massive or homogeneous to medium and small scale cross bedding in tidal bars, Ball (1967), is probably genetically unacceptable because the lower unit is formed by bioturbation. An exactly opposite sequence can be seen in the Meridian Sand (Wermund 1965), which likewise is supposed to be a tidal bar. Sequences in bars, given by Masters (1967) and McKee and Sterrett (1961), consist predominantly of cross-stratification, usually ranging from concave-up to low-angle-planar foresets. An upward decrease in coset thickness has been noted by Ball (1967) in offshore bars, and also by McDowall (1960) and Harms et al (1962) from alluvial deposits.

Table(8.8.3) Vertical sequences of sedimentary structures in alluvial sandstones from the Eocene of Texas ; after Fisher & McGowon (1969).

tributary channel facies (upstream)	highly meandering channel facies (downstream near delta)
horizontally laminated	horizontally laminated with ripples which are not generally preserved
	wedge set cross beds
festoons and wedge set cross beds and lag conglomerates	tabular set cross beds
	festoons and lag conglomerates

Table(8.8.3)

The four categories of alluvial deposits listed by Bernard and Major (1963), poor bedding, medium scale cross bedding, horizontal lamination and small scale cross bedding, were taken to show a vertical sequence (Shelton 1967) which is similar to the Coal Measures'sandstones. However, examination of the report of Bernard and Major's (1963) work showed that no such inference was made in the original paper. Fluvial facies in the Eocene delta in South-East Texas (Fisher and McGowon 1969) contain vertical sequences of sedimentary structures totally unlike the Westphalian sandstones.ᖲ

Although the upward sequence from massive to flat laminated or bedded, in deltaic levee deposits, is reminiscent of the Coal Measures' sandstones, the sequence from the intimately associated channel-fill facies, from silt-free cross beds to silty cross laminations, has not been recorded.

The interpretation of the upward sequence depends very much on the interpretation placed on each member, especially in the case of homogeneous sand. In some cases the interpretations are open to doubt. Furthermore, there are problems of scale attached to any comparison. For example, the tidal bar described by Ball (1967) is only 12 feet thick, so that repetition would be required to build a sand body of the dimensions of the Coal Measures belts. Repetition would destroy any significance in the sequence of internal structures.

8.8 (i) Delta-front sands

Of the five environments of modern sand deposition being considered in detail, delta-front sands have been omitted from the discussions of individual sedimentary structures, because the nature of the structures produced is dependent on factors other than the hydrodynamic environment.

ᖲ table (8.8.3)

In the Rhone Delta, Oomkens (1967) found that the difference in density between the incoming sediment-laden water and the recipient body of standing water was critical. Where the basin is marine the incoming water is less dense, whatever the load carried, and, therefore, tends to spread out over the surface of the standing water. Gradual mixing and settling gives rise to sediments of progressively finer grain sizes at greater distances from the mouth of the distributary. Wave energy redistributes this material into coastal bars. Where the body of water is fresh or brackish, mixing occurs immediately in three dimensions with the discharge. The bedload is, therefore, deposited at the distributary mouth, the stream flow is blocked and the distributary shifts to a new course.

Fluviomarine conditions produce well-sorted sands which are predominantly horizontally laminated. Scarce cross laminations are the product of wave action. There is an absence of homogeneity in the Rhone Delta (van Straaten 1959). Provided that the body of water is too small to allow wave action to be generated, fluviolacustrine conditions produce a cross-laminated sediment of silt and sand.

The Coal Measures contain predominantly a fresh or brackish fauna and only one marine band was present in the section under investigation. Even if a large body of standing water is postulated, it must, therefore, be fresh or brackish and only rarely marine. There is apparently no information regarding present day deltas being built into large bodies of fresh water, if indeed such an environment is in existence. However, the Cretaceous Wealdon delta, which has been extensively studied by Allen (1948, 1959), was evidently formed under such conditions, and the sedimentary structures produced in the delta slope and front deposits (Taylor 1962) can be tentatively set up as a yardstick against which to compare the Westphalian sandstones.

Taylor (1962) described an upwards regressive sequence of structures, in the Ashdown and Tunbridge Wells sands, from predominantly flat bedded and rippled with rare foresets, festoons and massive beds, to flat laminated with ripples and more common foresets and festoons. The sequence of structures in the sandstones of the Coal Measures, therefore, bears some similarity to that of the regressive sandstones in the Wealdon Delta, and a similar depositional environment may be proposed on the basis of this evidence. However, the Ashdown sandstone approaches sheet-form geometry (see sample distribution in Allen 1948) unlike the Westphalian belts.

8.9 Orientation of Sedimentary Structures

The orientation of sedimentary structures may be studied in relation to the long axis of the elongate sand body and the palaeogeography. From the literature and on an a priori basis it is possible to construct conceptual models for both relationships in the depositional environments proposed.

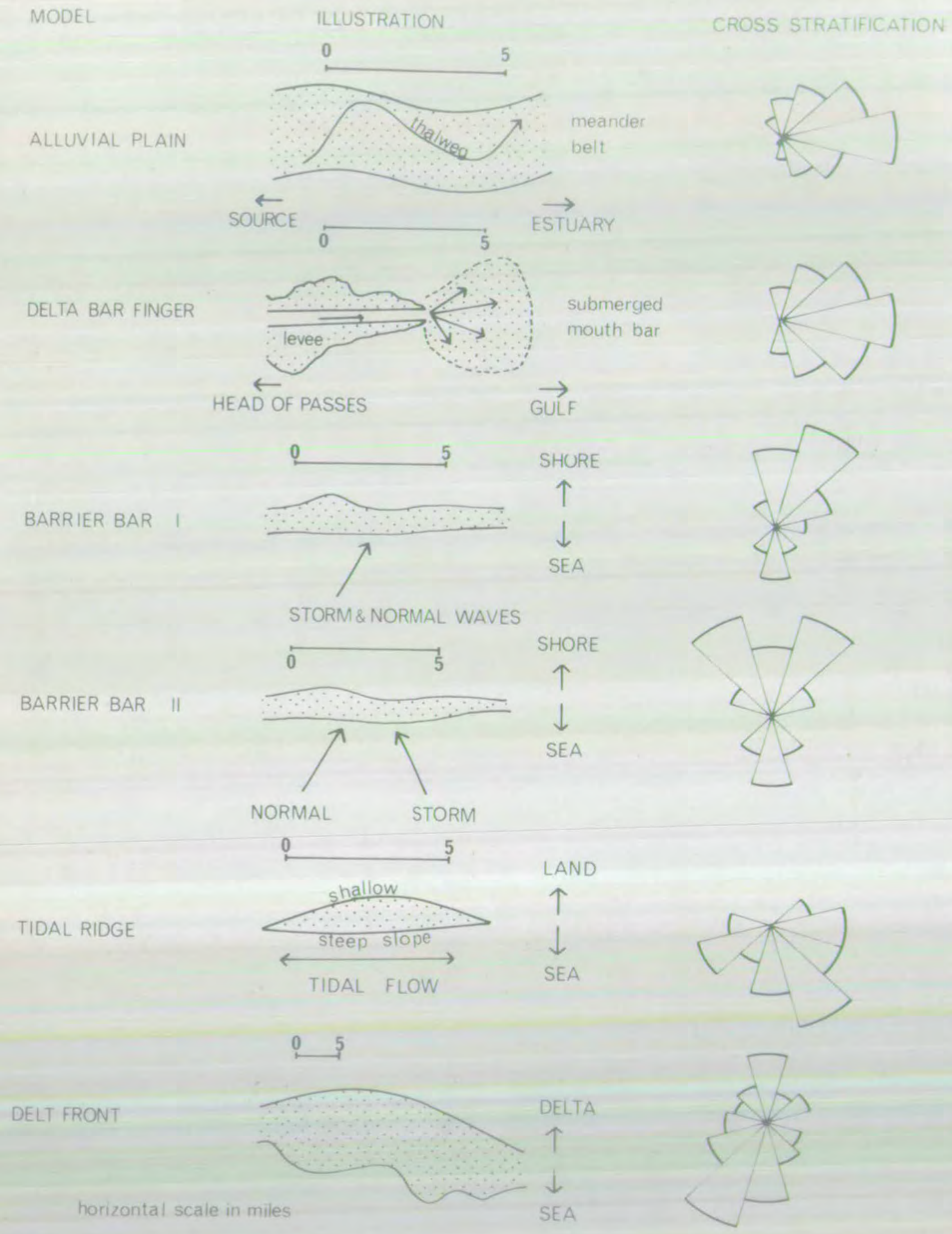
A river meandering in its alluvial plain constructs foresets predominantly on the downstream side of its point bars (McKee 1939). Cross-stratification is also produced by the downstream migration of sand waves, which have crests approximately at right angles to the direction of flow (Jordan 1962). The distribution of orientations should, therefore, have a mean sub-parallel to the axis of the meander belt (but see Kelling 1968) and a variance roughly proportional to the sinuosity of the thalweg. This model is similar to those given by Doty and Hubert (1962) and Allen (1965) for modern sands, and by Kelling (1968) for Westphalian channels in Wales.

In a bar finger or delta distributary model the mean of the distribution will be parallel to the long axis of the sand body and the variance will be a function of the shelf slope and discharge. Fisk (1960) stated that "the dip of the laminae...........radiate gulfward from the direction of flow in the distributary." In a similar model produced by Allen (1963) it was suggested that 84% of all the measurements would fall between 34° and 83° on each side of the mean.

Work by McKee and Sterret (1961), Masters (1967), Ball (1967), Bigarella (1965) and many others, has shown that the orientations of cross-stratification in longshore bars is, in general, oblique to the long axis of the sand body. Wave refraction, by topographic 'highs', gives rise to breakers or shoreward directed currents depending upon the depth of the obstacle. In both cases the result is the movement of sediment across the bar axis. Shoreward dipping foresets usually have a moderate angle of inclination, but low angle planar foresets, which dip seaward, can also be formed. Against this, Hoyt (1969) has suggested that most foresets dip seawards, including those of moderate and high inclination.

The variance of the distribution will be a function of the angle at which the waves impinge upon the shore and the effectiveness of the obstacle. In most shelf seas two sets of waves are common. The first set, of smaller waves, arises in the direction of maximum fetch and the other, usually much larger, in the direction of the main storm path. The former give rise to thin and the latter to thick cosets. It follows, therefore, that the variance will be proportional to the angle between these two sets of waves.

Recent work by Houbolt (1968) suggested that a similar model can be used for tidal sand ridges, although most foresets tend to dip towards open water. An earlier model proposed by Allen (1963), that the



MODEL
ILLUSTRATION
CROSS STRATIFICATION
0
5
ALLUVIAL PLAIN
thalweg
meander
belt
SOURCE
ESTUARY
0
5
DELTA BAR FINGER
levee
submerged
mouth bar
HEAD OF PASSES
GULF
0
5
SHORE
BARRIER BAR I
SEA
STORM & NORMAL WAVES
0
5
SHORE
BARRIER BAR II
SEA
NORMAL
STORM
0
5
LAND
shallow
TIDAL RIDGE
steep slope
SEA
TIDAL FLOW
0
5
DELT FRONT
DELTA
SEA
horizontal scale in miles

Figure(8.9.1)

orientation of structures is parallel to the tidal flow, must probably be discarded, although it has recently been restated by Shelton (1967). Small scale structures, orientated parallel to the ridge crests, have been shown to be formed by the topographic localisation of flow in the troughs (Ball 1967).

Cross-stratification can be produced in delta-front sands in a fluviolacustrine environment. The foresets dip offshore and, therefore, obliquely to the long axis of the sand body (Coumkens 1967). Cross-lamination in fluviomarine delta-front sands in the Wilcox Group in Texas was described as "multidirectional" by Fisher and McGowan (1969). For the reasons discussed in section (8.8 (i)) the fluviolacustrine model was used in the following study.

The six models, including the two bar variants, are summarised in figure (8.9.1).

Before proceeding further it should be noted that there are three possible sources of error in the comparison of the conceptual models with the actual data. In the first case, since two structures will not have the same "preservation potential" (Allen 1967) the actual distribution could be skewed compared to its correct theoretical counterpart. Secondly, although the sample was random in that it was located by exposure, it is possible that it could have been biased by its restriction to the strip of outcrop. Finally, the samples of sedimentary structures and belt orientations have been drawn from different parent populations within the sampling universe; the reason was the dearth of outcrop and the inability to handle greater quantities of subsurface data of increasingly lower standard. However, comparison of figure (8.9.2) with figure (8.6.4), suggests that the magnitude of the error will be small.

Table(8.9.3) To test for uniformity in orientation data from sedimentary structures and belt axes.

a) total sedimentary structure data

$$\text{vector mean} = \bar{x} = \tan^{-1}\left(\sum n_i . \sin x_i \,/\, \sum n_i . \cos x_i \right) = (180 - 80)^{\circ} = 95^{\circ}$$

$$\text{variance} = s^2 = (1 / (n-1)) . \left(\sum f_i . (x_i - \bar{x})^2 \right) = 6750$$

$$F_o = 10800 / s^2 = 1.6$$

therefore $F_{.05}(8,11) = 2.95 > F_o$

and distribution is not significantly non-uniform.

b) principal mode of sedimentary structure data

vector mean = 100° ; variance = 1124 ; $F_o = 9.6$

therefore $F_{.05}(8,8) = 3.4 < F_o$

and the distribution is significantly non-uniform.

c) orientation of sandstone belt axes

vector mean = 65° ; variance = 1284 ; $F_o = 8.4$

therefore $F_{.05}(8,5) = 4.82 < F_o$

and the distribution is significantly non-uniform.

a) Ungrouped data

class limits	axis frequency	structure frequency
0 to 29	5	2
30 to 59	11	6
60 to 89	12	20
90 to 119	2	32
120 to 149	2	12
150 to 180	1	4

$$U = 20.49 > X^2_{.05}(5) = 11.07$$

b) Grouped data

class limits	axis frequency	structure frequency
0 to 59	16	8
60 to 89	12	28
90 to 180	5	48

$$U = 17.98 > X^2_{.05}(2) = 5.99$$

Table(8.9.4) Analysis to test the null hypothesis that orientation and sample, belt axes and minor internal structures, are independent.

The mean vector of orientations of sedimentary structures (95°) cannot be accepted because the variance of the distribution is not significantly different from the expected value if it were uniform; table (8.9.3). The principal mode has an acceptable vector mean of 100°, which is appreciably different from that of the unimoded belt orientation data, of 65°.

Chi-square tests, table (8.9.4), show that in grouped and ungrouped data, there is a significant difference, at the 5% level, between the two samples. The alluvial and deltaic bar finger models must, therefore, be rejected because of the difference in orientations of belt axes and sedimentary structures. Of the three remaining models, the tidal ridge and delta-front sand are less likely because their principal modes point away from the nearest landmass. A barrier or offshore bar model is thus suggested by this line of inquiry.

8.10 Summary of Conclusions

Only a few of the many sedimentary structures have proved to have any environmental significance, and none of these can be taken as conclusive. The strongest evidence refers to associations of structures and operates with a negative sense.

The absence of trough-cross-stratification is argument against an alluvial origin, and especially a braided river system. Doeglas' (1962) syndrome, of festoons and planar cross-stratification with washouts, cannot be applied. Concurring, although less reliable evidence, is the presence of asymmetrical, probably oscillation, ripples. Similarly, the common thick bedding in cosets, debars a delta distributary origin.

In a positive sense, slightly discordant planar foresets have been reported from alluvial plains and barrier bars. However, in the Coal Measures sandstones they tend to dip in the opposite direction to foresets of higher discordance, therefore favouring a bar model.

Considering the type and frequency of minor internal structures, there is a tentative suggestion that the sandstones could have originated in a beach or a bar type environment. Comparisons with modern delta-front sands, which potentially can exhibit a wide range of sedimentary structures, are favourable and the Wealdon analogy is informative. The orientations of the sedimentary structures enhances the barrier bar hypothesis but does not favour the delta-front, or coastal barrier sand model.

No sedimentological aphorism has been derived from this study but the evidence from the sedimentary structures, and especially their orientations, points more consistently to a barrier bar model than any of the remaining four categories. From this study it has become clear that a much more rigorous technique is required for the study of modern and ancient sands, linking gross geometry with the nature and orientations of minor internal structures, grouped according to such characteristics as thickness or discordance.

8.11 Mineralogy and Texture

Mineralogically the Coal Measures sandstones are simple. According to Pettijohn's classification all the samples were felspathic greywaches, although analogues from Durham (Clarke 1963) and Northumberland (Jones 1955) have been described as orthoquartzites. The contradiction arises from the interpretation of the amount of matrix, which consists of clay sized material and limonite. The coarse fraction is predominantly quartz and felspar, with rare rock fragments, mainly clusters of quartz grains, bundles of mica flakes and grains of limonite, some of which are probably diagenetic.

Approximate quantitative diffractometry was used to estimate the felspar to quartz ratio of the whole rock. The ratio of peak heights, measured at $2\theta = 28^{\circ}$ and $42,4^{\circ}$, was computed for the samples and a synthetic standard (Doff 1969) containing equal amounts of quartz and felspar (Kaye <u>et al</u> 1968). From this data a conversion factor was computed and used to convert ratios of peak heights to ratios of concentrations. The factors and results are shown in table (8.11.1). Modal counts of the coarse fraction in thin section show much higher quartz felspar ratios, indicating that the matrix must contain much fine grained, possibly degraded felspar.

Diffractometer techniques used to identify monomineralic specimens of felspar, cannot easily be applied to sedimentary rocks where many species may be present. For the same reason statistical optical techniques used to identify plagioclases tend to be ambiguous. Probable optical identifications of orthoclase, microcline and sanidine were made in thin section. Plagioclase measurements suggested compositions in the range albite to oligoclase. Most samples contained some albite.

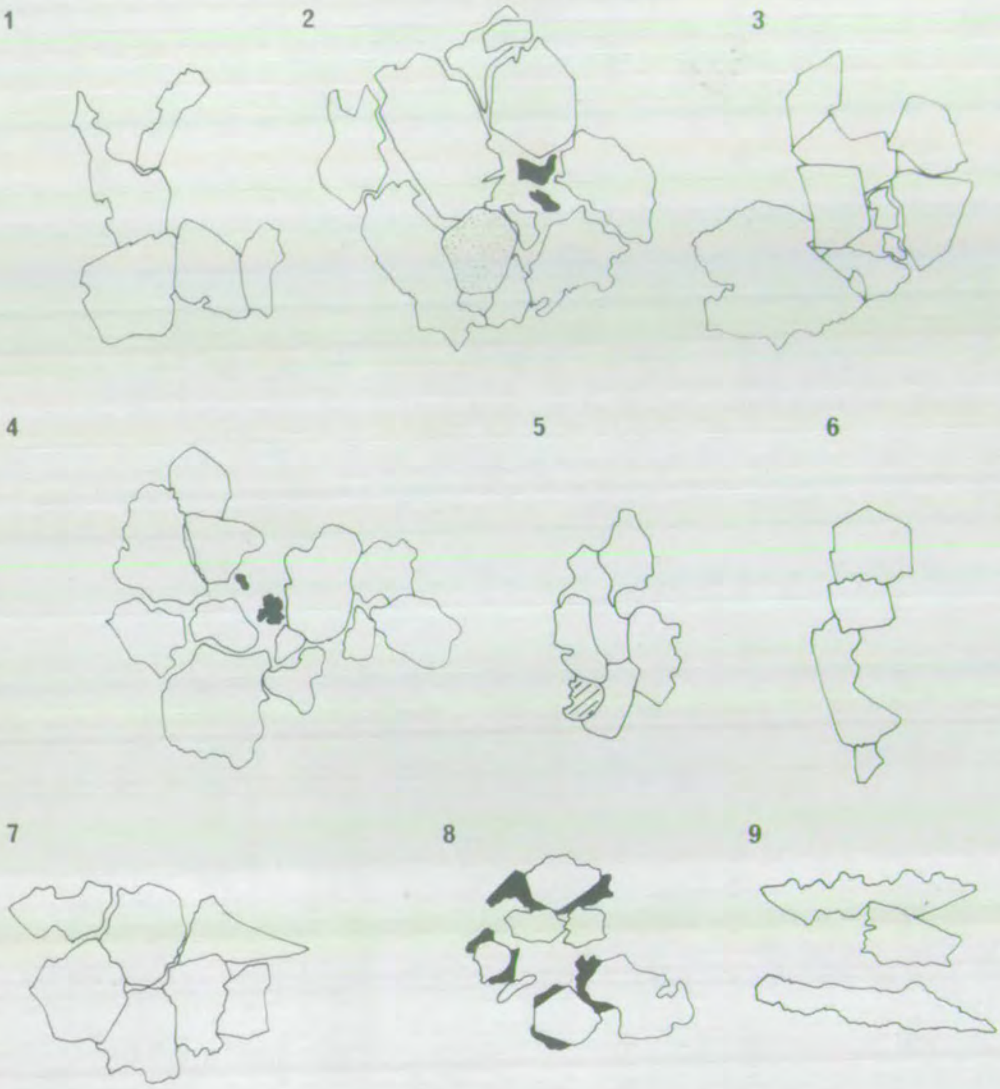
The most abundant detrital heavy minerals were picked out on the diffractometer trace, and shown to be zircon with rutile and anatase. Zircons seen in thin section were often euhedral with rounded corners, and did not seem to have suffered extensive attrition.

The felspars and heavy minerals indicate a mixed source, but the shape of the zircons suggests that these may not be second cycle sandstones.

Sample	Horizon	Felspar / Quartz ratio	
G1	Top Hard Rock	0.14	0.12
F1	Top Hard Rock	0.09	
TF4	Tupton Rock	0.14	0.13
TF3	Tupton Rock	0.12	
D1	Mainbright Rock	0.001	0.03
I1	Mainbright Rock	0.05	
C2	above High Hazles coal	0.07	

$$\left[\frac{\text{Felspar}}{\text{Quartz}}\right] = \frac{\text{Peak height } (2\theta = 28)^{\circ}}{\text{Peak height } (2\theta = 42.4)^{\circ}} \times 0.1$$

Table(8.11.1) Conversion factor between peak height (on the diffractometer trace) ratio and concentration ratio ; results from the East Midlands Coalfield.



contact	long	1,2,3,7
	sutured	1,6,7
	concavo convex	2,4,5
triangle intergrowth		1,3
embayment by matrix		all; notably 9
elongation		9
euhedra		early 1,2,3,6 ; late 8

□ quartz
▦ quartzite
▨ felspar
■ quartz late growth

Figure(8.11.2) Grain clusters illustrating the diagenetic history of Coal Measures sandstones. All sections x 50 magnification. Samples from the Roof Soft, Tupton and Deep Hard Rocks.

The shape of the quartz grains, typically angular or subangular, does not have any significance with regards to the depositional environment because they have undergone complex diagenetic alterations. Applying the terminology of Taylor (1950) and the concepts of Dapples (1967), the grain contacts, shown in figure (8.11.2), suggest that the rock has undergone the diagenetic stages listed below.

1) Growth of quartz grains in optical continuity, to give idiomorphic grains with long contacts and triangular intergrowths, was accomplished so that the original grain boundaries were obscured.

2) Pressure solution of quartz grains gave rise to sutured and concavo--convex contacts between grains, and the embayment of grains by the matrix. Some intergranular precipitation of quartz may have been associated with pressure solution. Elongation, parallel to the bedding, was created by pressure solution of quartz grains at contacts with the clay matrix. Solution was most pronounced at the top and base of each grain (Heald 1955, 1956).

3) A later stage of syntaxial growth, enclosed and sometimes formed euhedra. Many of the irregular patches of quartz in the matrix may have been formed during this stage.

The general lack of dust-rings, which would define the original detrital grains, admits the possibility that the euhedra may not be authigenic. However, the unabraded nature of most triangular facets suggests that the grains are not individually second cycle (Ojakanagas 1963). On the other hand, the suggestion of large, partly degraded, clusters of grains, see figure (8.11.2), implies that the first stage may not have occurred within the body of the present parent rock.

Size analysis by sieving was done on nineteen samples only. The results are shown in table (8.11.3). The average mean grain size,

Source	Structures	Geometry	N
Top Hard Rock	c f with r	sheet form	2
Top Hard Rock	c f no r	" "	6
Top Hard Rock	m t	" "	8
Top Hard Rock	c l	" "	9
Top Hard Rock	c f with l	" "	17
Top Hard Rock	x f	" "	18
Deep Hard Rock	x f	belt axis	3
Deep Hard Rock	m t	belt flank	10
Deep Hard Rock	m t	belt flank	11
Tupton Rock	m t	belt flank	12
Tupton Rock	m t	belt flank	13
Dunsil Rock	c f with r	?	1
Dunsil Rock	m t	?	7
Clay Cross Soft Rock	c f with x l	thin pod	4
Clay Cross Soft Rock	c f with c l	thin pod	5
High Hazles Rock	x f	?	14
1st. Ell Rock	x f	?	20
Crawshaw Sandstone	m t	?	16
Crawshaw Sandstone	x f	?	15

c conformable ; x cross-stratified ; r ripples ;
m massive ; l laminated ; f flaggy bedded ; t thick

Table(8.11.3) Data from the East Midlands Coalfield.

		moment measures				Trask measures			Doeglas indices %				
N	M	m	st	sk	kt	ST	SK	Md	1	25	50	75	99
2	0.054	4.2	1.56	0.41	1.61	1.32	0.86	0.082	3	4	4	5	7
6	0.067	3.9	1.57	0.57	2.04	1.36	0.88	0.093	3	4	4	4	7
8	0.102	3.3	1.71	0.53	2.69	1.28	0.97	0.112	2	3	4	4	7
9	0.063	4.0	1.59	0.70	2.36	1.38	0.90	0.090	3	4	4	4	9
17	0.067	3.9	1.62	0.64	2.42	1.35	0.88	0.095	3	4	4	4	8
18	0.083	3.6	1.64	0.69	1.85	1.44	0.83	0.114	3	3	4	4	7
3	0.083	3.6	2.11	0.30	1.02	1.48	0.94	0.096	2	3	4	4	10
10	0.077	3.7	1,74	0.80	2.64	1.29	0.95	0.101	3	3	4	4	8
11	0.058	4.1	1.61	0.77	2.55	1.33	0.69	0.099	3	4	4	5	8
12	0.109	3.2	1.73	0.92	3.65	1.28	0.88	0.150	2	3	3	4	8
13	0.112	3.1	2.29	0.78	2.13	1.46	0.75	0.205	2	2	3	3	9
1	0.067	3.9	1.78	0.39	1.25	1.40	0.99	0.076	3	4	4	5	8
7	0.063	4.0	1.69	0.73	2.37	1.32	0.77	0.118	3	3	4	4	7
4	0.088	3.5	1.91	0.51	1.34	1.50	0.97	0.087	2	3	4	5	10
5	0.109	3.2	1.54	1.13	6.16	1.29	0.97	0.149	3	3	3	4	10
14	0.083	3.6	2.05	0.63	1.76	1.36	0.89	0.113	2	3	3	4	9
20	0.088	3.5	1.63	0.92	3.68	1.22	0.91	0.139	2	3	3	4	7
16	0.134	2.9	1.47	1.29	8.47	1.18	0.95	0.167	2	3	3	3	8
15	0.218	2.2	1.74	1.08	6.51	1.27	1.09	0.280	1	2	2	3	8
a	0.081	3.7	1.76	0.67	2.44	1.36	0.88	0.114					

N reference number ; M mean, mm. ; m mean, phi ;
st, ST standard deviation ; sk, SK skewness ;
kt kurtosis ; Md median, mm. ; a average

Table(8.11.3)

a) To discriminate between groups with different sedimentary structures :-

cross-stratified vvs. homogeneous samples

$$D = -1.29.m - 3.09.st + 2.43.sk - 1.82.kt$$

$$F = 0.21 < F_{0.1}(4,5) = 3.52 \ \underline{\text{and}} < F_{.05}(4,5) = 5.19$$

b) To discriminate between groups from different sandstone bodies :-

Top Hard Rock vvs. Deep Hard Rock samples

$$D = -20.24.m - 73.05.st - 27.36.sk - 5.01.kt$$

$$F = 4.31 > F_{0.1}(4,4) = 4.11 \ \underline{\text{but}} < F_{.05}(4,4) = 6.39$$

Table(8.11.4) Discriminant function analysis amongst groups from the Coal Measures' data. N.B. since the number of samples is about the same as the number of variates, separations which arise may not be justifiable.

D discriminant function value ; m mean grain size in phi units ; st standard deviation ; sk moment skewness ; kt moment kurtosis.

excluding the two examples from the Crawshaw Sandstone, was 0.081 m.m. The greatest mean size, 0.112 m.m., and the smallest, 0.054 m.m., show that on Wentworth's scale most samples fall into the fine sand group and the rest are coarse silts.

The median grain size was greater than the mean for all samples. The cause was positive skewness. The average Trask sorting coefficient was +1.45 and the moment equivalent +1.76. In general terms these results show that while the coarse fraction is well sorted, the sand as a whole is poorly sorted. The moment and Trask skewness values, 0.67 and 0.88 respectively, show that the average distribution has an extensive fine tail.

Together these results indicate that the sands now consist of two distinct components, a well sorted coarse fraction and a muddy matrix. This conclusion is summarised by the leptokurticity of all the samples.

Discriminant function analysis was used to show that, at the 10% level of significance, whereas groups of samples with different minor internal structures had the same size distributions, those from different sandstones did not; table (8.11.4). Source is, therefore, a more important factor than hydrodynamic environment. The samples used were very small and no great reliance can be placed on this calculation.

U.S.A. grain size data from bodies of known geometry, was compiled, table (8.11.5), and the geometric groups, 'sheet' and 'channel', were compared with each other and with the Coal Measures' data, table (8.11.6). Although many of the sources of error, discussed below, will operate in the same direction in a comparison of weight per cent, sieve data of predominantly Carboniferous sandstones, the geological implications must be treated with care. Furthermore, the results may not be statistically meaningful since

Source	Geometry	N
Anvil Rock Sandstone	sheet	F
Mississippian sandstones	all sheets	K
Degonia Sandstone	sheet	M
Caseyville Sandstone	sheet	N
Trivoli Sandstone (finer)	belt (channel)	A
Trivoli Sandstone (coarser)	belt (channel axis)	B
Inglefield Sandstone	belt (channel fill)	C
Pleasantview Sandstone	belt (channel fill)	D
An Oligocene Sandstone	belt (delta plain)	E
Anvil Rock Sandstone	channel	G
Matoon Sandstone	channel	H
Vermilionville Sandstone	channel	I
Palzo Sandstone	belt	J
Mississippian sandstones	all elongate	L

F	Hopkins (1958)	average of 15
K	Potter (1963)	average of 7
M	Biggs *et al* (1955)	1 sample
N	Biggs *et al* (1955)	average of 3
A	Andresen (1961)	average of 5
B	Andresen (1961)	average of 15
C	Andresen (1961)	average of 3
D	Rusnak (1957)	"typical"
E	Nanz (1954)	"average"
G	Hopkins (1958)	average of 30
H	Bradbury *et al* (1962)	1 sample
I	Bradbury *et al* (1962)	1 sample
J	Bradbury *et al* (1962)	1 sample
L	Potter (1963)	average of 9

Table(8.11.5)

		moment measures				Trask measures			Doeglas indices %				
N	M	m	st	sk	kt	ST	SK	Md	1	25	50	75	99
F	0.072	3.8	1.60	0.82	3.02	1.81	0.86	0.137	1	2	3	4	10
K	0.134	2.9	2.28	0.80	2.58	1.36	0.84	0.131	2	3	3	4	9
M	0.095	3.4	2.32	0.81	2.56	1.32	1.06	0.106	2	3	4	4	7
N	0.077	3.7	1.69	0.67	2.34	1.23	1.08	0.161	2	3	3	3	9
A	0.095	3.4	2.06	0.73	2.53	1.36	0.82	0.102	3	3	4	4	8
B	0.081	3.6	2.46	2.83	0.01	1.31	0.92	0.192	1	3	3	3	9
C	0.137	2.9	2.11	0.84	3.16	1.43	0.96	0.200	1	3	3	3	9
D	0.104	3.3	1.99	0.79	2.89	1.29	0.88	0.085	3	4	4	5	9
E	0.081	3.6	2.16	0.53	1.33	1.43	0.75	0.170	2	3	3	4	9
G	0.105	3.3	2.15	0.75	2.64	1.38	0.86	0.281	2	2	2	3	9
H	0.085	3.6	1.71	0.73	3.23	1.46	0.77	0.215	2	2	3	3	9
I	0.192	2.4	1.59	0.13	0.55	1.63	0.85	0.122	2	3	4	4	10
J	0.097	3.4	1.68	0.52	2.35	1.51	0.80	0.179	2	3	3	4	9
L	0.152	2.7	1.53	0.79	6.18	1.33	0.94	0.178	2	3	3	4	5

N reference symbol
M mean, mm.
m mean, phi
st, ST standard deviation
sk, SK skewness
kt kurtosis
Md median, mm.

Table(8.11.5)

a) To discriminate between U.S.A. sheet and channel groups.

$$D = 1.95.m + 1.17.st - 0.93.sk + 0.17.kt$$

$$F = 0.33 < F_{0.1}(4,9) = 2.69 \ \underline{\text{and}} \ < F_{.05}(4,9) = 3.63$$

b) To discriminate between U.S.A. channel and total East Midlands Coalfield groups.

$$D = -2.68.m + 2.21.st + 0.53.sk - 0.42.kt$$

$$F = 2.41 > F_{0.1}(4,24) = 2.33 \ \underline{\text{but}} \ < F_{.05}(4,24) = 2.78$$

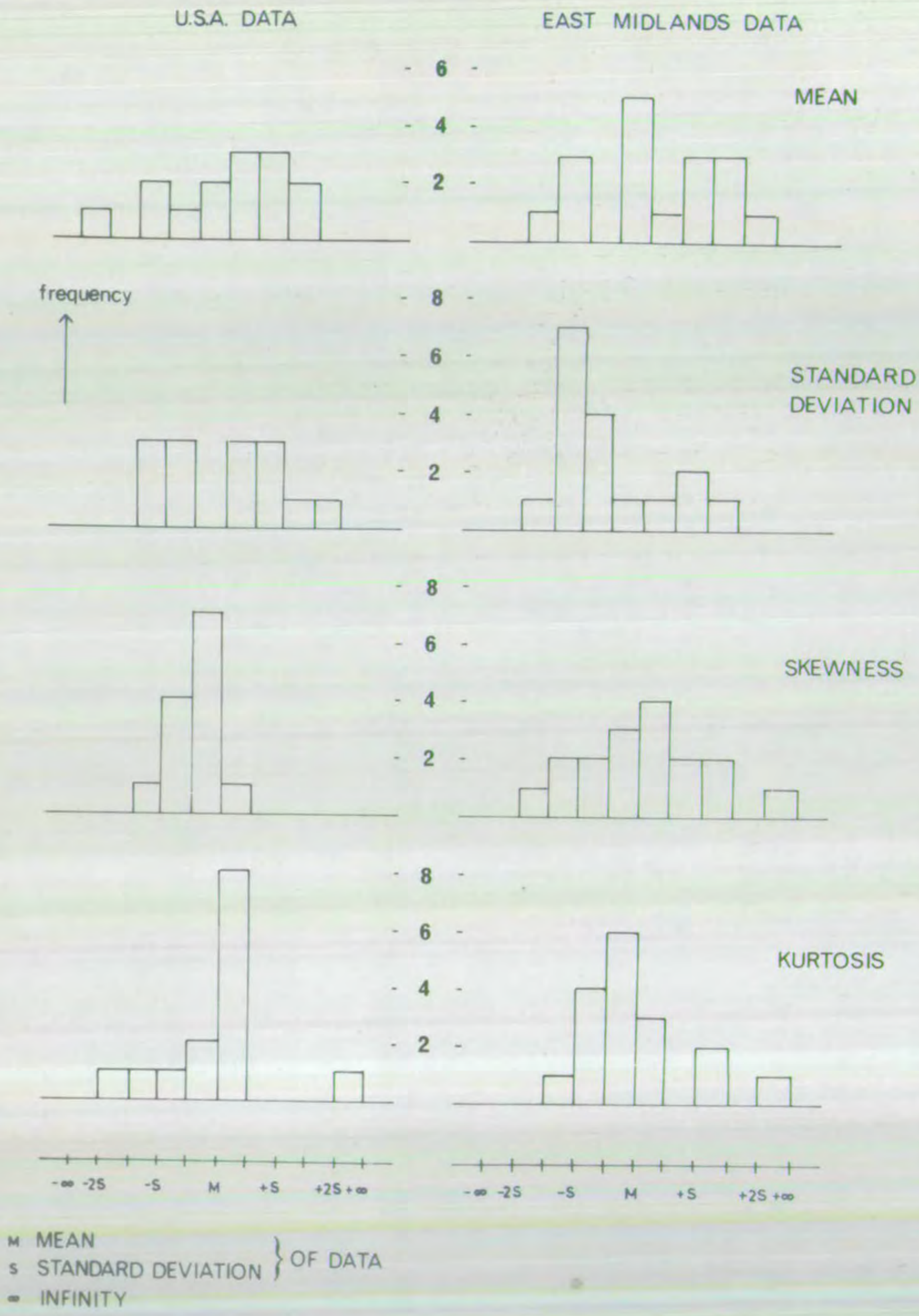
c) To discriminate between U.S.A. sheet and total East Midlands Coalfield groups.

$$D = 1.52.m + 5.58.st + 6.74.sk - 0.38.kt$$

$$F = 1.16 < F_{0.1}(4,18) = 2.29 \ \underline{\text{and}} < F_{.05}(4,18) = 2.93$$

Table(8.11.6) Discriminant function analysis between U.S.A. and British groups.

D discriminant function value ; m mean grain size in phi units ; st standard deviation ; sk moment skewness ; kt moment kurtosis.



Figure(8.11.7) Size/frequency distributions of textural data submitted to Discriminant Function Analysis.

the variables should be normally distributed. It was not possible to test for normality because of the small size of the samples. According to Clarke (1957), assumptions or normality, necessary for conveniently small samples, are unlikely to cause error which is technically significant. The data was, therefore, assumed to be normal, although the histograms shown in figure (8.11.7), do not always support this.

The results, tabulated in table (8.11.6), suggest that while, at the 10% level, the American 'sheet' and 'channel' groups are not different, the Coal Measure group is significantly different from the American 'channel' and yet similar to the 'sheet' group. Potter's (1963) interpretation of 'sheet' sandstones as marine regressive and 'channel' as alluvial cut and fill, tentatively suggests that the grain size data and apparent gross geometry are contradictory. However, there are many possible modes of origin for belt sandstones.

It is impossible to extrapolate backwards in time from the present to past effective size distributions. The principal reasons are listed in table (8.11.8). However, the errors, apart from imponderables, all tend to work in the same direction so that the present moment measures, based on a phi scale, will all be larger than their counterparts in the original sediment. A confirmatory example is given by Chappell (1967) who described the skewness of beach sands increasing from -1, to 0, to +1, from the Recent to the Upper and Lower Pleistocene of a restricted area.

The principal factor is the overemphasis of the fine tail. Comparison with recent work (for example Friedman (1967)) on present day sands is, therefore, totally ambiguous, when the whole distribution is considered. However, much less error is involved if only the central part of the distribution is used, as for example by Doeglas (1968) whose

a) <u>Mechanical Errors</u>

i) grain clusters ; incomplete disaggregation
ii) grain fracture
iii) variable sieve mesh size and shape
iv) effect of grain shape on ability to pass a sieve
v) effect of authigenic limonite , in the matrix and as a coating on grains, on weight % measurements.

b) <u>Errors Arising During Diagenesis</u>

i) Felspars preferentially and extensively degraded ; original size distribution may have been different from that of the quartz grains.
ii) solution of, and growth on, detrital grains
iii) authigenic grains

c) <u>Imponderable Theoretical Errors</u>

i) aggradation state of clay fraction at time of deposition is unknown
ii) physical and chemical state of depositing medium is unknown ; eg. therefore, thickness of clay adsorbed water layers is unknown.
iii) effect of i) and ii) on viscosity and, therefore, on the size distribution of the coarse fraction.

Table(8.11.8) Some possible sources of error in the interpretation of the grain size distributions of sandstones.

three figure indices (Q_1 : Md : Q_3) are wide enough to take up much of the error arising during diagenesis and lithification. No Coal Measures' sandstone has an index which falls in an exclusively river sand category, whereas all samples with a median index of 4 correspond with a group containing shallow marine, tidal flat, lagoon and bay and deeper marine sands. Doeglas states "..... 344, 446, 455, 556, indices, the series would be coastal marine."

The errors listed in table (8.11.8) should not greatly alter any original variation in mean grain size upwards through a sandstone body. Four of the modern geometrical models, alluvial plain, barrier bar, delta-front sand and distributary bar finger, are supposed to show significant variations in grain size in vertical section. Allen (1964) said that the fining upwards characteristic of alluvial sediments was fundamental. However, Fisher and McGowon (1968) found that some fluvio-deltaic sandstone bodies do not fine upwards. Bars and delta-front sands tend to coarsen upwards (Sabins 1963, Berg and Davies 1968, Oomkens 1967). This feature is produced by vertical growth which accentuates shoaling and, therefore, may not be ubiquitous. The downward increase in silt content in bar finger and mouth bar sands, as described by Fisk (1961), gives rise to an overall upward increase in grain size.

These criteria have been applied to ancient sand deposits by Nanz (1954). Although Potter (1963) concluded that the "..... combined data indicate that elongate sand bodies become finer upwards", when considering the Carboniferous of Illinois, Kosanke et al (1960) had already decided that "..... the uniform texture, sorting and bedding throughout considerable thickness of sandstone suggest marine sedimentation rather than stream deposition", in a study of the Pennsylvanian of the same State.

Similarly, Bass (1936) recorded no vertical variation in grain size in shoestrings from the Carboniferous of Kansas.

Maximum sizes of quartz grains, measured in thin section from samples collected at the localities used to compound the vertical sections shown in tables (8.6.1) and (8.6.2), do not show any simple trend. However, in terms of the frequency of interbedding of silt or mud with sand, many of the bodies, recorded in recent boreholes, tend to fine upwards in their thickest parts. The data shown in table (8.11.9), was used in an analysis of variance, table (8.11.10), to test the hypothesis that fining-upwards sandstones are thicker than non-fining-upwards. The result shows that there is a marked difference at all levels of significance.

The simple allusion to an alluvial origin is complicated by the complex fining characteristics of the flanks of the main belt. The bar or barrier bar and distributary models are unfavourable when considered from this standpoint.

If, in conclusion, any confidence can be had in inference from grain size analysis, comparison with ancient analogues suggests that the Coal Measure Sandstones are marine regressive, and with modern sands that they were coastal marine. The fining characteristics, in terms of maximum grain size, bear comparison with ancient offshore bars (Bass 1936) but their uniformity contrasts with modern bars, and also delta-front sands, which tend to coarsen upwards.

Borehole	Fining Characteristic	Thickness	Separation	from Underlying coal
68203	fud	137	0	RS
	c(s)	11	0.6	DH
67406	fu	22	0.5	RS
	fd	24	1.5	DH
	c(s)	13	0.5	DHR
	fd	16	4	Pk
	c(ss)	10	4	Ck
	fu	54	7	T
65301	fu	31	0.1	RS
	c(s)	15	5	DS
	fud	17	0.6	DH
	fd	19	16	Pk
	fu	98	0	T
65103	fud	6	0.3	RS
	fc	14	10	DS
	fud	12	12	Pk
	c(ss)	112	0	T
57302	c(ss)	8	13	DS
	c(ss)	5	6	DHR
	c(ss)	11	18	DH
	s/ss	22	9	Pk
	fud	37	31	T
78301	fc	21	0	RS
	fd	56	12	DH
	c(ss)	22	0	Pk
68201	fu	100	0	RS
69401	fud	87	63	RS
	fu	76	0	Pk
	fd	13	7	P2
	fd	12	6	TRf
	fu	21	5	Tq
69201	fd	15	21	DS
	fc	106	0	Pk
	fd	13	5	Th
65102	fd	10	3	BnR
	fud	16	0.5	TS
	s/ss	15	11	RS
	fud	9	14	Pk
68302	fu	14	24	Ch
	fu	15	16	DS
	fu	114	0	Pk
	fud	36	11	Th
77103	fud	8	2	TS
	fd	6	19	RS
	c(s)	23	0	DHR
	fud	9	3	DH
	fu	28	0	Pk
	fd	95	8	T

Table(8.11.9)

Borehole	Fining Characteristic	Thickness	Separation from	Underlying coal
68402	fd	32	2	RS
	fu	140	0	Pk
	fd	11	0	TRf?
68101	fud	12	4	TS
	fud	62	0	RS
	fud	15	2	DHR
	fud	21	0	DH
	c(ss)	25	7	Pk
	fd	16	3	T
64401	fu	118	0	T
64201	fd	13	5	TS
	fd	20	2	RS
	fud	16	14	DS
	fud	22	2	P2
	c(s)	18	0.5	T
63307	fd	16	?	BlR
	fd	15	0.5	DS
	fd	16	3	DH
	fd	26	8	Pk
	fud	15	2	P2
	fud	47	0	T
68304	fu	50	3	RS
	c(s)	25	21	Pk
67202	fud	9	2	TS
	fud	27	3	RS
	fud	20	4	DH
	fd	48	1	Pk
67404	fud	26	4	RS
	s/ss	74	0	DH
	fd	33	0	Pk
	fd	30	2	Ck

Table(8.11.9) Fining characteristics of Coal Measures' sandstones, from recent data.

fu	fining upwards
fd	fining downwards
fud	fining upwards and downwards
fc	fining centrally
c(s)	constant grain size, siltstone
c(ss)	constant grain size, sandstone
s/ss	interbedded or interlaminated siltstone and sandstone

Source	SS	df	MS	F
Between Groups	17525	1	17525	19.6
Within Groups	29443	33	892	
Total	46968	34		

$$F = 19.6 > F_{.05}(1,33) = 4.11$$

Table(8.11.10) Analysis of variance among thicknesses of sandstones which do and do not fine upwards.

SS sum of squares

df degrees of freedom

MS mean square

8.12 Synthesis

The characteristics of the Coal Measures sandstones have been collated with modern sediments. Other ancient sandstones have also been considered but the Recent comparisons have been taken to be of overriding importance. A study of the gross geometry produced the most unified set of results; none favoured an alluvial or bar finger origin and all suggested deposition as barrier bars. Examination of the internal structures produced more ambiguous results because most of the examples considered could be produced in any of the geometrical models under consideration. However, the coexistence of low angle planar foresets, oscillation ripples, homogeneous bedding, common horizontal lamination and bedding, and the absence of trough cross-stratification, was taken to suggest, but not prove, that the Coal Measures' sandstones were deposited as barrier bars or delta-front sands. Comparison of the measured orientations of the minor internal structures with conceptual models for each of the five categories, showed that only one, the barrier or offshore bar, was statistically acceptable. Diagenetic complications were found to rule out the possibility of any concrete inference from textual studies.

The implications of comparisons with Recent sediments have been condensed into table (8.12.1). On a simple for and against basis the evidence points to formation as barrier or offshore bars. This conclusion would be enhanced if the more ambiguous arguments from analogy, concerning the internal geometry, were less heavily weighted.

There is no overall background of previous work against which these conclusions can be assessed. Apart from cyclicity (see Duff et al 1967) and some regional and general studies (for example Trueman 1954, Clarke 1963,

Sandstone characteristics	F	A	D	B	T
Sedimentary structures:-					
i) moderate angle, concave up foresets in planar cosets.	@	@	@	@	@
ii) trough cross-stratification	o	-	o	o	?
iii) low angle planar foresets in planar cosets.	@	@	?	@	?
iv) thin bedding	?	@	@	@	?
v) thick bedding	?	o	-	@	?
vi) conformable bedding & lamination	@	@	@	@	?
vii) homogeneous bedding	-	?	@	@	?
viii) flaser bedding	?	?	-	?	?
ix) wave ripples	@	-	@	@	@
x) current ripples	@	@	@	@	@
xi) erosional phenomena, washouts	@	@	@	@	?
xii) conglomerates etc.	@	@	-	@	?
xiii) plant debris	@	@	@	?	?
xiv) shelly fauna	@	@	o	o	?
xv) upward sequence of structures	@	?	?	?	?
xvi) orientation of structures	-	-	-	@	o
Gross geometry:-					
i) orientation of belts relative to nearest shoreline	@	-	o	@	o
ii) pattern of belt axes	@	o	o	@	-
iii) discontinuity	@	-	-	@	@
iv) thinning characteristics	?	o	-	@	@
Texture					
i) vertical variation in grain size	?	o	-	-	?
ii) vertical increase in % silt	-	o	-	-	?
iii) grain size parameters	?	?	?	?	?
iv) grain shape	?	?	?	?	?

Table(8.12.1) Synthesis of the evidence connecting the Coal Measures' sandstones with modern environments which produce elongate sand bodies. F delta front ; A alluvial plain ; D delta distributary ; B barrier or offshore bar ; T tidal ridge ; @ for ; - against ; o equivocal ; ? insufficient modern data.

Sylvester - Bradley and Ford 1968, Murchison and Westoll 1968, Coalfield Memoirs of the Geological Survey) the detailed sedimentology of the Pennine Basin has been neglected. Recently, however, Elliott(1965, 1968, 1969) has investigated this aspect of the Coal Measures in depth. Careful analysis into 10 sedimentary facies has led Elliott (1968 figure (4), 1969) to an interpretation in terms of distributaries. The sandstone belts mentioned by Elliott (the Tupton (1968 figure (1)), High Hazles and Top Hard Rocks (1969 figures (3,4))) all trend North-East along the presumed depositional strike, and thus the difference of opinion clearly do not arise from inconsistencies in the Coal Measures' data.

Clarke (1963) made the unsubstantiated statement that sandstone body elongation is in the "direction of cross-strata", and, therefore, unjustifiably used an alluvial model thereafter in his paper. This study referred to the Northumberland and Durham Coalfield, where earlier work by Jones (1955) had already shown that all the sand bodies considered were elongate in a direction oblique, and in some cases orthogonal, to that of the cross-stratification.

That there are almost as many hypothesis as studies, is a reflection upon the complexity of Westphalian geology, which may be in turn a symptom of the large amount of available data compared to other Systems and Stages.

It is noteworthy that the sandstones of the East Midlands Coalfield can almost be considered copies of shoestrings in the Cherokee Shale of the Pennsylvanian of Kansas (Bass 1936). Similarity but not congruence of gross geometry is supplemented by the correspondence in type and orientation of the minor internal structures. Bass' (1936) conclusion that the shoestrings were formed as barrier bars is illustrated by his palaeogeographic reconstruction, figure (8.12.2).

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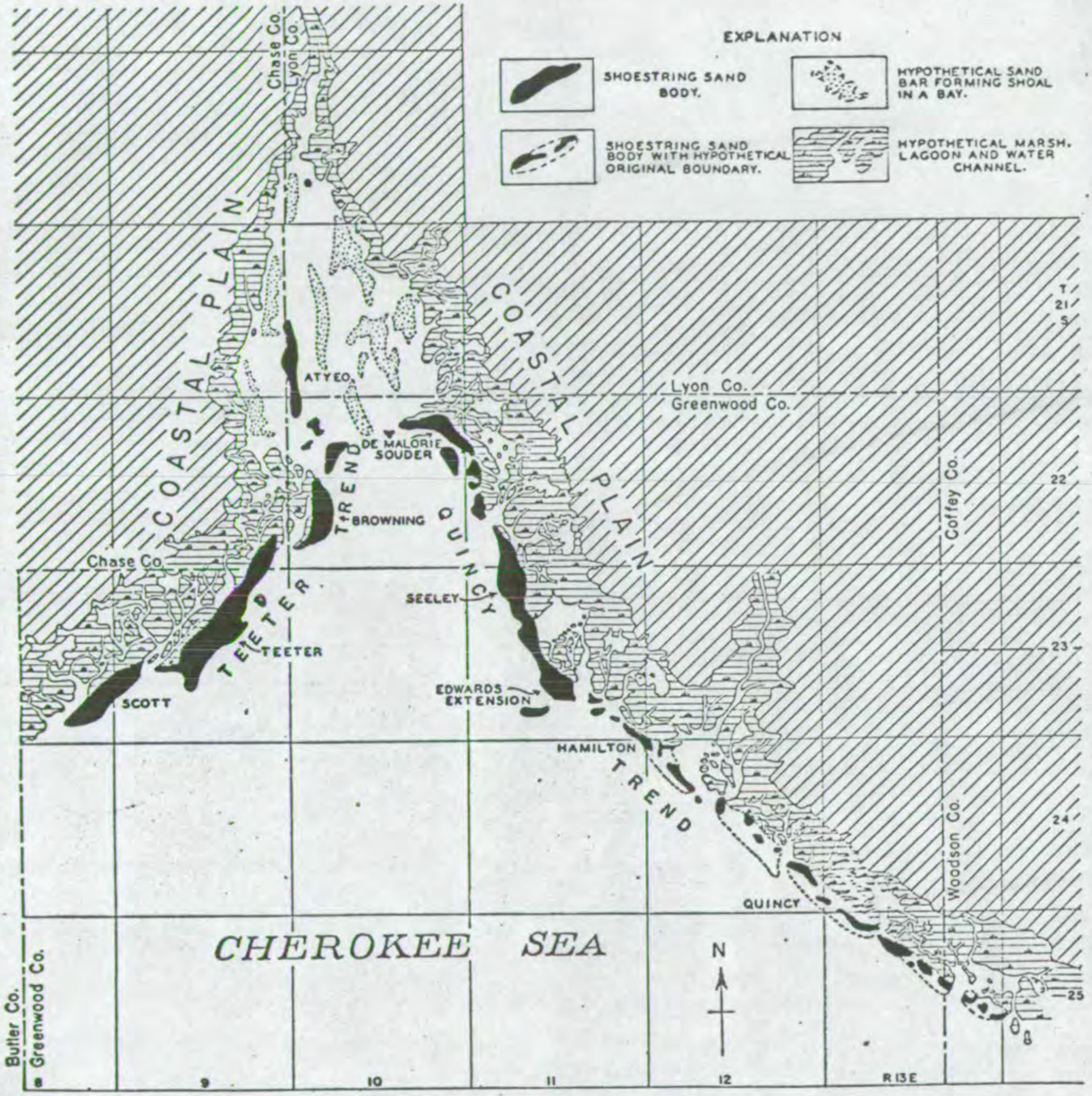
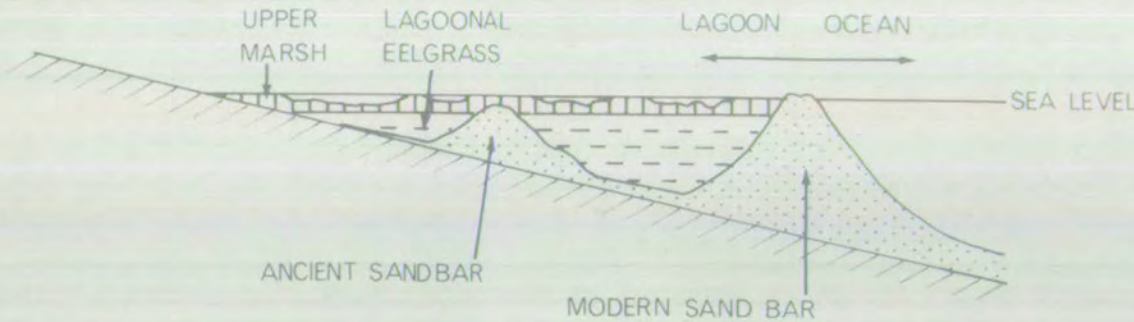
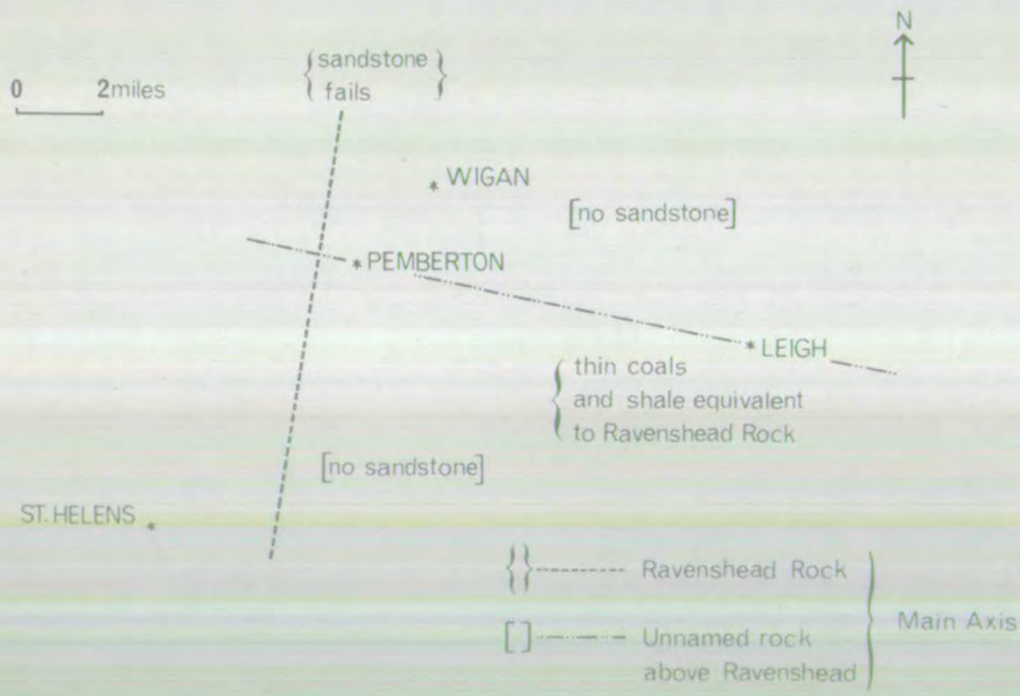


Plate 19. Hypothetical sketch of a part of the Greenwood-Butler county region during the Teeter-Quincy stage of the Cherokee sea. (Sand bodies are known from records of wells; other features are hypothetical.)

Figure(8.12.2) A palaeogeographic reconstruction of barrier bar sandstone bodies ; from Bass(1936).



Figure(8.13.1) Burial of sand bars by lagoonal deposits. After Shaler(1885).



Figure(8.14.1)

8.13 Problems in Accepting Some Conclusions

It is difficult to reconcile the characteristics of Coal Measures sediments with the hypothesis that the sandstones were formed as barrier bars, since such structures typically divide marine and lagoonal environments. The restriction of marine fauna in the Communis and Modiolaris Zones to a single band suggests that any body of standing water would have been fresh or brackish. The lack of asymmetry of the non-marine fauna about the belt axes, therefore, does not present any insuperable problems, but lithological symmetry, in all except thickness, cannot simply be explained by uniform salinity.

Lithological consistency could arise as a normal by-product of the building and preservation of the sandstone belts. Bars, formed during still-stands or at hinge lines, are often associated with thick lagoonal deposits, without thick basinal equivalents. During regression, the site of bar formation moves down the depositional slope. The old bar is then buried and preserved in lagoonal deposits. This model, shown in figure (8.13.1), is based upon Shaler's (1885) description of Plum island, Massachusetts.

There is evidence to support this hypothesis. The divided belts of the Deep Hard Rock are of different ages, the down-dip branch being younger than its up-dip counterpart. A similar relationship holds between sandstone belts in the Tupton to Parkgate interval. Furthermore, the Deep Soft Rock 'c' was clearly buried under an appreciable thickness of coal-bearing sediment before termination of the interval.

The symmetry problems associated with the barrier bar hypothesis can, therefore, be resolved if construction was at the margin of a large, fresh water body during a period of net regression.

8.14 Sandstones of other Parts of the Pennine Basin

The geometry of sandstones, at equivalent stratigraphic horizons, has been studied from the descriptions of coalfields in the Pennine Basin other than the East Midlands.

The area immediately to the North of the East Midlands Coalfield (Mitchell et al 1947) contains the extension of the Parkgate Rock belt, figure (4.4.4). A cross-section, comprising Aldwarke Main, Warren House, Kilnhurst, New Stubbin and Carr House collieries, shows that the sandstone thins downwards from the areas of greatest thickness. The Trencherbone Rock, the Lancashire equivalent of the Parkgate Rock, similarly thins downwards (Tonks et al 1931, figure 9). Washouts associated with this sandstone trend North-North-East near Wigan (Jones et al 1938) and, therefore, parallel the isopachs of the total Coal Measures (Wills 1956). Using criteria established in the East Midlands the sandstone body should also trend North-North-East. The Ravenshead Rock also parallels the depositional strike but an overlying sandstone is oblique, figure (8.14.1).

Washouts under the Bullhurst Rock of the Potteries Coalfield (Evans et al 1968) suggest elongation along the depositional strike, and the Banbury Rock, in the same area, appears to thin up the depositional slope.

In the Northumberland and Durham Coalfield the sandstone bodies are elongate and trend East-North-East (Jones 1955, Smith et al 1967). It is difficult to gauge the significance of this trend because no total isopachs are available for comparison. However, Kent (1967) has stated that the Coal Measures extend across the whole of the southern North Sea (see also Bartenstein 1968). If these sediments are an extension of the Pennine Basin then the total thickness isopachs, which trend North through Yorkshire, could swing to an East-West orientation in Northumberland and Durham.

The Harvey Rock in the Durham Coalfield is a notable exception. The dendritic pattern of the 50 feet isolith suggests either a northerly prograding delta distributary or a southerly flowing river (Smith et al 1967).

In all the above-mentioned coalfields, with the addition of Warwickshire and Leicestershire (Trueman 1954, Sylvester-Bradley et al 1968), the gross geometry is reasonably constant. Widths of 2 to 5 miles are typical and thicknesses in excess of 120 feet are rare.

On the basis of this scant evidence, there is apparently no reason for assuming that most of the sandstones, in the Communis and Modiolaris zones of the Pennine Basin, were formed in radically different ways from those found in the East Midlands area. Geometrical studies are necessary in all the Pennine Basin coalfields before a comprehensive depositional system can be proposed with any certainty.

8.15 Palaeogeographic Implications

If the elongate sandstone bodies of the East Midlands Coalfield were formed as delta distributaries, alluvial valleys or alluvial plains, the sense of the orientation of the minor internal structures suggests that the source of sediment should lie to the South-West of the East Midlands area. The ultimate source must, therefore, be the Midland Barrier. However, this landmass was an island or peninsula less than 100 miles wide (Wills 1951, Bartenstein 1968), see figure (3.0.2).

It is difficult to imagine how sufficient discharge could be generated, by such a small catchment area, to maintain Mississippi size bar fingers or to produce flow depths in a river of the order of 40 feet, as indicated by the thickness of some of the cosets (Allen 1963).

If a delta model is proposed, then whether the sandstone bodies were delta-front sands (a Rhone or Niger model) or bar fingers (a Mississippi type model) there should be associated fluvial and delta-plain facies. In the Rhone model these facies should occur in the South-East, and in the Mississippi model somewhere to the South-West of the East Midlands Coalfield. Using Fisher and McGowen's (1969) synthesis of deltaic environments, such facies would be characterised by elongate sandstone bodies with dendritic patterns or, nearer the delta front, by individual meandering ribbons of sandstone. The elongation would be in the direction of cross-stratification and point down the depositional dip. The sedimentary structures in these sandstones would be of the type illustrated in ~~figure~~ table (8.8.3). There is no evidence for the existence of this facies in the study area or in the Leicestershire, South Derbyshire, Warwickshire and Forest of Wyre Coalfields (Trueman 1954, Sylvester-Bradley et al 1968).

Models in which the sandstone belts are formed as bars do not present such extreme source problems. Bars are often fed from the 'seaward' side although ultimately some material may be derived from the adjacent landmass (Johnson 1919, Colony 1932). Local derivation is not essential because material can be moved over very large distances by longshore drift.

The tidal ridge model could be constructed on the same lines as the North Sea (Houbolt 1968) if free passage of water through the Hereford Straits is possible. However, it is most likely that any standing water in the Pennine Basin was fresh or brackish and it follows that there can have been little or no free connection with the open sea, except during marine incursions. Tidal mechanisms cannot, therefore be proposed to account for the construction of sandstone bodies which are entirely surrounded by non-marine sediments. The absence of tides would also tend to rule out a Mississippi or Ganges type delta in which lobes of sediment grow out into a depositional basin (Kruit 1969, personal communication).

CONCLUDING REMARKS

The raison d'etre for the research programme described in this thesis was to identify and evaluate the geological forces which gave rise to the nature and dispositions of the sedimentary rocks which make up the Coal Measures of the East Midlands Coalfield. In as far as the results of any non-experimental investigation can be considered decisive, these objectives have been met with a reasonable degree of success.

In the first place, the fact that Coal Measures' successions can be broken down into natural, sedimentological units ('intervals') has importance beyond making possible a study of stratigraphic relationships: it shows that in amongst the oft-mentioned variability of coal-bearing successions there exist more systematic elements, which can be interpreted in terms of Westphalian palaeogeography and other features.

Studies of the areal distribution of thicknesses of the intervals have shown that some patterns exist which reflect subsidence in the Pennine Basin as a whole. Taken together with the fact that the number of cycles increases (by means of coal splits) towards the centre of the Pennine Basin, the correspondence shows that basinal downwarping was continuous, although occasionally overshadowed by controls of a smaller areal extent.

Like the surrounding intervals, the intervening coals thicken towards the centre of the Pennine Basin. The simple patterns of coal isoliths are frequently disrupted in areas corresponding to the position of the major sandstone body(ies) of the preceding interval. Disruption takes the form of acute thinning, sometimes so that an otherwise thick coal is represented by only a seatearth, and frequent splitting.

The separation of the scale components of variance made it possible to show that in many cases significant negative correlations exist between the thicknesses of adjacent intervals, on both the large (regional) and moderate (local) scales. The repetition of the negative correlations suggests that if they are produced solely by subsidence there must have been complete and perfect reversals of the subsidence pattern on all scales, so that areas of maximum subsidence for one interval become areas of minimum subsidence for its successor before becoming unstable yet again. This concept is unwelcome because of its complexity. In addition, although it is impossible to disprove tectonic control (for small scale variability), the fact that the orientation of elongate local components is orthogonal to the trend of pre-Permian structural features makes it again necessary to postulate a more complex tectonic history than is warranted by other, independent lines of inquiry. Furthermore, the loci of local thickness maxima shift from interval to interval (and hence give rise to negative correlations) unlike the fixed local pattern which would be imposed by a tectonic control (eg. fault basins etc.)

Comparison of the dispositions of sedimentary facies with the thickness patterns shows that the negative correlations can be explained in terms of compaction of the substrate concurrent with, and possibly caused by, the accumulation of the sediments of the subsequent interval. The more clayey parts of the substrate are potentially more compactible than sandier parts, and it can be argued that space created in this way can give rise to above average thicknesses of later sediment. Since the sandstones of adjacent intervals tend to be offset relative to each other, the system under which they were deposited must be influenced by a control (differential compaction) which at the same time is giving rise to negative correlations on the large scale.

The interplay of regional downwarping with differential compaction has been suggested previously by other authors, but no attempt has been made to assess the validity of the hypothesis. In response to the existence of this deficit, a simulation model of the compaction of Coal Measures' sediments was constructed, and so designed that any errors involved would serve to overestimate the contribution from differential compaction. Consequently the results, which indicated that compaction is totally inadequate to explain the observed inverse proportionality, are highly significant.

Fortunately, a detailed study of the Coal Measures' sediments has shown that it is unnecessary to revert to the complex and artificial subsidence control hypothesis.

Individual sandstone bodies are often thicker (and even much thicker) than their lateral equivalents, even allowing for compaction. Unless the sandstones had considerable topographic expression over the enclosing sediments (which is unlikely) they must have been progressively emplaced during the period of their accumulation. The complex nature of the areal distribution of the sandstone bodies renders it most unlikely that they were formed by the infilling of hollows created by subsidence. It follows that subsidence must have been caused by the weight of the accumulating sediment (sand predominantly). The patterns of the sandstone bodies can, therefore, be considered to be controlled by the depositional system, and offset between sandstone bodies of adjacent intervals (and sub-intervals) could have given rise to the negative correlations, on the local and occasionally regional scales, without additional contribution from compaction or subsidence motivated by an external mechanism. However, negative correlations on the large scale also exist where sandstones are restricted in areal extent and thickness. In this case it is necessary to propose some mechanism which would cause the locus of maximum potential instability to shift from interval to interval, so that subsidence as a response to widespread sedimentation could produce the regional negative correlations. A mechanism of this type has been proposed recently by Collette (1968).

Positive correlations arising on the regional scale are probably caused by an increase in the instability of the Pennine Basin which allows downwarping to override other factors. The single positive correlation on the local scale arose between interval 1, with almost no sandstone, and interval 2, where thick sandstones are very widespread.

If it is to be accepted that in some cases the gross geometry of the Coal Measures' sediments was partly controlled by the depositional system, offset must be a creature of the environment in which the sandstones were formed. Recent work in the U.S.A. has re-emphasised that Carboniferous coal-bearing successions were laid down in a deltaic environment (Wanless et al 1963, Swann 1964). Elliott (1968,1969) has also suggested a deltaic origin for the Westphalian of the Pennine Basin. It is difficult to envisage how offset and parallelism could be generated in a Mississippi-type Delta although they could be produced by the superimposition of delta-front sand bodies.

Evidence from the gross geometry of the East Midlands sandstone bodies pointed consistently to an origin as barrier bars and not as delta-distributary or delta-front sands (or alluvial sands or tidal and offshore bars).

Other sources also support the barrier bar hypothesis but do not exclude the alternatives. With a few exceptions (see Bass 1936) the sandstones of the Pennine basin are, therefore, unlike their counterparts in the U.S.A., and it seems reasonable to accept the results of studies of modern sediments (see for example Dapples and Hopkins 1969) which indicate that coal could have been formed in both coastal and deltaic environments.

Empirical evidence from recent work (for example Fisher and McGowan 1969) can be taken to show that parallelism and offset can arise naturally in a barrier bar system through time. In some cases, and perhaps in every case, parallelism could be the result of a constant pattern of basinal subsidence, since this uniformity would serve to maintain parallel hinge lines. Grouping and offset could also be caused by the control on the location of sand deposition by buried sand bodies. This control operates through the attenuation of peats resulting from posthumous subsidence associated with the accumulation of sand bodies. At the sediment surface, peat is unstable and will over-compact in response to an imposed sediment load. Thus, a thin sheet of sediment spread evenly over a peat swamp will exhume any buried sand mounds because of the reduced peat thickness. Initially, the deposition of sand could then be controlled by the accentuated shoaling over the exhumed mound, although the principal site of early accumulation would be shifted away from that of its predecessor because of the extra space created by continuing over-compaction.

So far, speculation regarding the mechanism which promoted cyclicity in the sedimentary successions in the East Midlands' Coal Measures has been avoided, because it seemed illogical to compare selected examples from the Carboniferous with, for example, a generalised sequence from the Mississippi Delta. However, the results of this research programme indicate that in the East Midlands area cyclicity could not have been caused by tectonism, delta-switching or compaction, and that the hypothesis of marine inundation by the breaking of barrier bars must be rejected, because in the instances where such bars are found the enclosing sediments show no trace of asymmetry.

The forces controlling cyclic sedimentation should be sought amongst those governing the nature and dispositions of the sediments. In the East Midlands' Coal Measures the principal regional control was BASINAL DOWNWARPING, and the principal local control was a DEPOSITIONAL ENVIRONMENT dominated by the location of BARRIER SAND BARS and catalysed by the OVER-COMPACTION of PEAT. These results do not exclude the possibility of other (eg. botanical) controls operative on the small scale.

The clastic sediments were probably accumulated during a period of net regression in which (? back-bar) lagoonal deposits containing thin seams of peat overlapped and buried the sand bars. Short periods of clastic sedimentation were interspersed with extended periods during which the larger part of the Pennine Basin contained peat swamps. The marked restriction of marine faunas suggests that the sand bars were built on the margins of a large fresh-water body; this model is more in keeping with the almost complete enclosure of the North European Westphalian Basin (Bartenstein 1968).

APPENDIX 10

C O M P A C T I O N

10.1 List of Symbols

e	void ratio
ea	effective void ratio
w	water content, % of dry weight
W	water content, % of wet weight
n	porosity
V	total volume of any increment <u>cc</u>
M	total weight of any increment <u>gms</u>
Vs	volume of the solid phases <u>cc</u>
Ms	weight of the solid phases <u>gms</u>
Vw	volume of the liquid phase <u>cc</u>
Mw	weight of the liquid phase <u>gms</u>
VA	volume of the gaseous phase <u>gms</u>
d	average specific gravity of a whole increment, allowing for hydrostatic uplift <u>gms/cc</u>
dw	specific gravity of liquid phase <u>gms/cc</u>
ds	specific gravity of solid phases (average) <u>gms/cc</u>
P	pressure due to overburden <u>kg/cm^2</u>
p	pressure due to a single increment <u>kg/cm^2</u>
av	coefficient of compressibility <u>cm^2/gm</u>
mv	coefficient of volume compressibility <u>cm^2/gm</u>
cv	coefficient of consolidation <u>cm^2/sec</u>
k	coefficient of permeability <u>cm/sec</u>
r	compaction ratio between Westphalian rocks and original sediment, in initial state near the top of the sediment pile.

(o) postscript to any symbol to indicate the initial state

(i) postscript to indicate the i th. state, usually i increments down from initial state

(z) postscript, state of Westphalian rocks

D prefix, to indicate a change in a parameter from one state to the next.

10.2 Some Relationships

$$r = \frac{1 + e(o)}{1 + e(z)} \qquad \text{(a)}$$

$$av = \frac{e(o) - e(i)}{DP} \quad cm^2/gm \qquad \text{(b)}$$

$$mv = \frac{av}{1 + e(o)} \quad cm^2/gm \qquad \text{(c)}$$

$$cv = \frac{k}{mv \cdot dw} \quad cm^2/sec \qquad \text{(d)}$$

$$d(i) = \frac{ds(i) - 1}{1 + e(i)} \quad gms/cc \qquad \text{(e)}$$

$$e(i) = \frac{Vw(i)}{Vs(i)} \qquad \text{(f)}$$

$$w(i) = \frac{e(i) \cdot 100}{ds} = \frac{Mw(i) \cdot 100}{Ms(i)} \qquad \text{(g)}$$

$$W(i) = \frac{100 \cdot w(i)}{100 + w(i)} \qquad \text{(h)}$$

$$n(i) = \frac{100 \cdot e(i)}{1 + e(i)} \tag{j}$$

ds = 2.65, for sand

ds = 2.7, for silt and clay

ds = 1.5, for peat

10.3 Anomalous Fluid Pressures

From equations 1.2(b), 1.2(c) and 1.2(d), it is possible to derive the equation

$$k = \frac{e(o) - e(i)}{DP \cdot (1 + e(o))} \cdot cv \cdot dw \quad \text{cm/sec.}$$

100 feet of clay at compactional equilibrium is composed of 286 increments, and thus from the model,

$e(o) = 5.3 \qquad P(o) = 0.01 \quad kg/cm^2$

$e(286) = 0.94 \qquad P(285) = 3.72 \quad kg/cm^2$.

A clay with a liquid limit of about 80% dry weight, as used in the model, has

$cv = 1.10^{-5} \quad cm^2/sec$

according to Terzaghi et al (1967). Therefore, assuming that dw is unity

$k \simeq 2.10^{-9} \quad cm/sec$,

and thus the hydraulic conductivity is $k \cdot 10^3$ or 2.10^{-6}.

10.4 Pressure Exerted by Each Increment

The initial increment can be considered to be under a load of 0.01 kg/cm^2, which is slightly higher than the figure given by Richards (1962) for the overburden stress at a depth of 30 cm, in what is probably a less highly colloidal clay than that proposed for the model.

Assuming the initial increment to consist of a solid and liquid phase,

$$V(o) = Vw(o) + Vs(o) \quad cc. \qquad (a)$$

and thus incorporating equation 1.2(f)

$$V(o) = Vs(o) \,.\, (1 + e(o)) \quad cc,$$

or $$Vs(o) = V(o) / (1 + e(o)) \quad cc.$$

Therefore $$Vs(o) = 30.48 / (1 + 5.3) = 4.83 \; cc.$$

If it can be assumed that,

$$DVs = Vs(i) - Vs(o) = 0$$

$$Dds = 0 \quad , \quad Ddw = 0$$

and that $dw = 1$ for the water of the liquid phase, then in state (i)

$$e(i) = \frac{Vw(i)}{Vs(i)} = \frac{Vw(i)}{Vs(o)}$$

It follows that

$$Vs(i) = e(i) \,.\, Vs(o) \quad cc,$$

and since $V(i) = Vw(i) + Vs(o)$ cc,

then $$V(i) = Vs(o) \,.\, (1 + e(i)) \quad cc.$$

From equation 1.2(e), the specific gravity allowing for hydrostatic uplift, the weight of the i th. increment can be computed from,

$$M(i) = d(i) \,.\, V(i) \quad gms.$$

Thus $$M(i) = \frac{(ds(o) - 1)}{(1 + e(i))} \,.\, Vs(o) \,.\, (1 + e(i)) \quad gms$$

and $$M(i) = (ds(o) - 1) \,.\, Vs(o) \quad gms.$$

Therefore $$p(i) = \frac{(ds(o) - 1) \,.\, Vs(o)}{1000} \quad kg/cm^2$$

and for clay

$$p(i) = \frac{(2.7 - 1) \cdot 4.83}{1000} = 0.008 \text{ kg/cm}^2.$$

For silt

$$Vs(o) = 30.48 / (1 + 1.2) = 13.48 \text{ cc},$$

and thus $$p(i) = \frac{(2.7 - 1) \cdot 13.48}{1000} = 0.023 \text{ kg/cm}^2.$$

For sand

$$Vs(o) = 30.48 / (1 + 0.7) = 17.9 \text{ cc},$$

and thus $$p(i) = \frac{(2.65 - 1) \cdot 17.9}{1000} = 0.029 \text{ kg/cm}^2.$$

10.5 Volume Reduction of Peat

In the Top peat

$$V(o) = Vs(o) + Vw(o) + VA(o),$$

and at a depth of 30 feet, which is equal to 60 increments

$$V(60) = Vs(60) + Vw(60) + VA(60).$$

Making the false assumption that $DVs = 0$ and the reasonable assumption that $VA(60) = 0$

$$V(60) = Vs(o) + Vw(60).$$

At the surface

$$W(o) = \frac{Mw(o)}{Mw(o) + Ms(o)} = \frac{Vw(o)}{Vw(o) + Vs(o) \cdot ds(o)}$$

$$= 0.9$$

and at 30 feet

$$W(60) = \frac{Vw(60)}{Vw(60) + Vs(o) \cdot ds(o)} = 0.7$$

assuming that $Dds = 0$, $Ddw = 0$ and $dw(o) = 1$.

Therefore $Vw(o) = 9 \cdot Vs(o) \cdot ds(o)$

and $Vw(60) = 2.3 \cdot Vs(o) \cdot ds(o)$.

Now $V(60) = V(o) / 5 = 30.48 / 5 = 6.1$ cc

so that $Vs(o) + Vw(60) = 6.1$ cc,

and thus $Vs(o) = 6.1 / (2.3\, ds(o) + 1) = 1.38$ cc.

It follows that $Vw(60) = 4.76$ cc.

Now since $(Vw(o) + Vs(o) + VA(o)) = 5 . (Vw(60) + Vs(60))$

or $Vs(o) . (9 . ds(o) + 1) + VA(o) = 5 . Vs(o) . (2.3 . ds(o) + 1)$

then $VA(o) = Vs(o) . (2.5 . ds(o) + 4) = 10.7$ cc.

Therefore, $Vw(o) = V(o) - Vs(o) - VA(o) = 18.2$ cc.

Where $ea(i) = Vw(i) / Vs(i)$,

the surface density, allowing for hydrostatic uplift

$$d(o) = \frac{ds(o) - 1}{1 + ea(o)} = 0.035 \text{ gms/cc}$$

and at 30 feet

$$d(60) = \frac{ds(o) - 1}{1 + ea(60)} = 0.11 \text{ gms/cc.}$$

At the surface

$$M(o) = (Vs(o) + Vw(o)) . ds(o) = 0.69 \text{ gms}$$

and at 30 feet

$$M(60) = (Vs(o) + Vw(60)) . ds(60) = 0.67 \text{ gms.}$$

The respective pressures per increment,

$$p(o) = 0.00069 \text{ kg/cm}^2$$

$$p(60) = 0.00067 \text{ kg/cm}^2.$$

For practical purposes

$$p(o) = p(60) = 0.00068 \text{ kg/cm}^2.$$

Employing linear interpolation, the rate of decrease of increment volume is given by

$$\frac{30.48 - 6.1}{30 . 2.54 . 12} = 0.027 \text{ cm/cm.}$$

By iteration it can be shown that the final volume, 6.1 cc, is reached after 60 increments. The overburden pressure on the bottom interval is, therefore, 59 . 0.00068 kg/cm^2 or 0.041 kg/cm^2.

10.6 Consolidation Rate

From Terzaghi et al (1967), the following parameters can be defined.

t	=	necessary time for U% consolidation	secs.
U	=	% of compaction to equilibrium	
Tv	=	dimensionless time factor	
H	=	half thickness of compacting layer	cm
cv	=	coefficient of consolidation	cm^2/sec

Assuming the boundary conditions for the consolidation of clay under its own weight in an open system, it is possible to obtain the estimates

$$Tv = 5.0 \quad \text{for} \quad U = 100\%$$

$$Tv = 0.2(4) \quad \text{for} \quad U = 50\%$$

from Terzaghi et al (1967), fig. 25.4(b), curve 'c_1'. Where cv = 10^{-5} cm^2/sec (appendix 10.3) and h is the thickness of the clay layer in feet, the relationship

$$t = \frac{Tv\ H^2}{cv} \quad \text{secs} \quad \text{(Terzaghi et al, 1967)}$$

can be adapted, for geological purposes, to

$$t = 3.68\ h^2 \ \text{years} \quad \text{for} \quad U = 100\% \qquad \text{(a)}$$

or

$$t = 0.15\ h^2 \ \text{years} \quad \text{for} \quad U = 50\% \qquad \text{(b)}$$

provided the following assumptions are permitted ;

(1) k and mv are constant in depth and time (appendix 10.1)

(2) drainage is vertical (only partially true)

(3) the time lag in reaching compactional equilibrium is caused by low permeability and not by the resistance to shear of adsorbed water.

appendix 11

LIST OF SUBSURFACE DATA

abbreviations

COLL.	COLLIERY
BH.	BOREHOLE
UGBH.	UNDERGROUND BOREHOLE
UC.	UPCAST
DC.	DOWNCAST
O.C.	OPENCAST SITE

34403	39504	47007	DENBY COLL. NEW WINNINGS SHAFT
34405	39675	48206	DENBY HALL COLL. NO. 1 SHAFT
34407	39234	49319	FORDS BH.
35203	39820	54880	ALFRETON GOLF LINKS COLL.
35206	39380	51830	PENTRICK COLL. SHAFT
35207	38745	50403	UPPER HARTSHAY NORTH PIT
35402	39360	55321	ALFRETON GOLF COURSE BH. R M 5
35403	39925	59915	MICKLEY BH.
35404	39888	58002	SHIRLAND COLL. NO. 1 SHAFT
35407	39270	56670	UFTONFIELDS BH.
35408	38936	55368	WINGFIELD MANOR COLL. DC. SHAFT
36201	39740	60330	AINTREE O.C. BH.
36204	39480	63860	CLAY CROSS NO. 1 KILBURN PIT
36401	39280	67940	CLAY CROSS AVENUE NO. 9 COLL.
37102	34960	74280	NESFIELD COLL.
37103	33800	74200	NEWGATE O.C.
37104	34900	72900	OVERHOLME O.C.
37201	36950	74880	ALBERT COLL. NEWBOLD
37202	37990	70100	BOYTHORPE COLL.
37203	39600	72700	BRIMINGTON BALMOAK + FISH O.C.
37204	36200	72300	FOLLY HOUSE O.C.
37206	39140	70010	HASLAND COLL.
37207	39260	70900	HADY HILL COLL.
37208	37770	73210	HIGHFIELD COLL. NEWBOLD
37210	36080	73220	NEWBOLD COLL.
37211	38750	73030	TUPTON COLL. LOCHOFORD NO. 1 PIT
37303	34710	75970	MONKWOOD COLL. NEW PIT
37401	38120	78610	APPERKNOWLE COLL. + BH.
37402	36400	75250	COBNOR WOOD NO. 3
37407	37713	77774	SUMMERLEY HALL O.C. BH. R H 5
37408	37654	77523	SUMMERLEY HALL O.C. BH. R M 6
37410	37900	75200	WHITTINGTON SIEGE O.C.
44101	41614	44140	MANCHESTER WOOD BH.
44102	42302	43344	MAPPERLY COLL. NO. 2
44103	40708	43137	SMALLEY GREEN BH.
44105	44132	42470	WEST HALLAM COLL. NO. 1 SHAFT
44108	44060	42463	WOODSIDE COLL. NO. 3
44106	43566	43385	WOODSIDE COLL. UGBH. 1
44107	44795	44373	WOODSIDE COLL. UGBH. 3
44202	47905	44022	BENNERLY COLL.
44204	47813	42676	COSSALL COLL. NO. 2
44206	45884	42454	MANNERS COLL. NO. 2
44208	48825	42536	OAKWOOD GRANGE COLL.
44211	45068	43282	SHIPLEY COLL. AIR PIT
44212	49618	40540	SHORTWOOD BH.
44311	43869	48227	PLASTIC NO. 3 BH.
44302	43391	47439	BAILEY BROOK COLL. WEST SHAFT DC.
44304	43185	45101	COPPICE COLL. NO. 1
44307	44660	46410	NEW LANGLEY COLL.
44308	42552	46406	NEW LANGLEY COLL. BH.
44312	40512	49937	RIPLEY COLL. NO. 3

44313	44603	49163	STONEYFORD BH.
44401	46430	48770	BRINSLEY COLL. NO. 1
44412	46516	48906	SELSTON COLL. BRINSLEY DRIFT
44404	46221	45784	EASTWOOD NO.3 PIT
44405	46526	47537	EASTWOOD HALL BH.
44406	47422	45305	LODGE COLL. DC. SHAFT
44409	47911	47837	MOORGREEN COLL. NO. 2
44410	48614	46144	NEW LONDON COLL.
44411	46183	47976	PLUMTRE COLL.
45101	41392	51984	BRANDS COLL.
45112	41549	51793	WESTERN PIT
45104	43200	51900	IRONVILLE NO. 4 OIL WELL
45105	44860	54485	PINXTON NO. 2 SHAFT
45106	44732	52267	PYEHILL COLL. DC. SHAFT
45107	43300	54381	SHADY PIT BIRCHWOOD COLL.
45109	41503	54600	SWANWICK COLL. NEW PIT
45111	44130	54290	UPPER BIRCHWOOD COLL.
45201	49573	51173	ANNESLEY COLL. UGBH. B3
45202	48769	54969	BENTICK COLL. NO. 2
45203	46221	54753	BROOKHILL COLL.
45204	45771	52791	NEW SELSTON COLL. DC. SHAFT
45301	41713	56338	ALFRETON COLL. NO. 1 SHAFT
45304	43534	55746	CARNFIELD WOOD BH.
45306	41280	58710	DOG LANE FARM BH.
45309	43625	55630	IRONVILLE NO. 2 OIL WELL
45305	42614	55013	COTES PARK COLL. NO. 1 SHAFT
45310	42643	57547	NORMANTON BROOK BH.
45401	45394	57727	BLACKWELL B WINNING COLL.
45402	49689	57784	KIRKBY COLL. UGBH. K6
45403	47467	55085	LANGTON COLL. NO. 7 SHAFT
45404	48335	57631	NEW HUCKNALL COLL. UGBH. BLACKSHALE
46101	40130	64400	CLAY CROSS COLL. NO. 2
46102	40952	63131	CLAY CROSS COLL. NO. 7 PARKHOUSE
46103	40100	64300	CLAY CROSS WORKS BH.
46105	41355	60376	CLAY CROSS COLL. NO. 5 MALON
46106	42638	63124	PILSLEY COLL. NO. 2 SHAFT
46107	44254	60089	TIBSHELF COLL. NO. 1 PIT
46201	49843	64335	PLEASLEY COLL. SOUTH PIT
46202	48955	64833	PLEASLEY COLL. UGBH. B2
46203	47133	61620	SILVERHILL COLL. NOS. 1 + 2 PITS
46204	46401	64228	SILVERHILL COLL. UGBH. 1
46205	47581	64116	SILVERHILL COLL. UGBH. 2
46206	47330	63722	SILVERHILL COLL. UGBH. 3
46207	46703	62747	SILVERHILL COLL. UGBH. 4
46208	48369	60179	SUTTON COLL. NO. 2 SHAFT
46210	45095	60930	TIBSHELF COLL. NO. 4 SHAFT
46301	41300	66120	ALMA COLL.
46302	42050	67900	BONDSMAIN COLL. NOS. 1 + 2
46303	40700	69500	CALOW BROOK NO. 1 O.C.
46304	40380	65400	CLAY CROSS NO. 4 COLL.
46305	41205	67686	GRASSMOOR COLL. NO. 1

46306	43583	65720	HOLMWOOD COLL. NO. 2 WINDING SHAFT
46308	42740	66608	WILLIAMTHORPE COLL. NO. 1 SHAFT UC.
46402	46500	66750	GLAPWELL COLL. NO. 3 SHAFT
46403	45097	66190	MILL LANE STAINSBY BH.
47102	41886	74670	DOWELL COLL. NO. 1
47103	41900	71400	DUCKMANTON MOOR FARM O.C.
47104	43370	72150	INKERSALL TOM LANE BH.
47105	43755	74169	IRELAND COLL.
47106	43450	74170	IRELAND COLL. UGBH. 6
47201	46087	71031	BOLSOVER COLL. NO. 2 SHAFT
47202	49420	71650	BOLSOVER COLL. BH. 4
47203	45380	70302	BOLSOVER COLL. UGBH. 10
47204	45013	72305	MARKHAM COLL. NO. 4
47205	45950	74315	MARKHAM COLL. UGBH.
47301	44610	76770	BARNHOUSE BH.
47302	41110	75870	CAMPBELL COLL.
47303	43360	75340	HARTINGTON COLL.
47305	42230	78540	HORNTHORPES COLL.
47308	43230	77580	RENISHAW PARK NO. 4 SHAFT
47310	42180	76750	WHITE LODGE BH. STAVELY
47311	40200	75900	WHITTINGTON BALLARAT COTTAGES O.C.
47312	40300	75300	WHITTINGTON MERRIANS O.C.
47401	49168	78374	CARR PLANTATION BH.
47402	46619	77195	COTTAM COLL. BH.
47403	48360	76060	OXCROFT NO. 3 COLL.
47404	47360	75040	ROMELEY HOUSE BH.
47405	47010	79650	WESTHORPE COLL. UGBH. 1
48101	44700	84620	BEIGHTON COLL.
48102	42270	84130	BIRLEY EAST PIT
48104	41470	82060	OWTHORPE O.C. BH. B2
48103	44384	81267	HOLBROOK COLL.
48201	45431	84224	BROOKHOUSE COLL.
48202	49290	82690	KIVETON PARK COLL.
48203	48940	84120	KIVETON NO. 1 BH.
48204	46504	81840	NORWOOD COLL.
48206	45190	80205	WESTHORPE COLL. UGBH. 2
48302	42406	87099	HANDSWORTH NUNNERY COLL.
48303	40230	89050	TINSLEY PARK COLL. UC. SHAFT
48401	46700	86100	BROOKHOUSE COLL. UGBH. 1
48403	49100	89100	THURCROFT MAIN COLL. NO. 2
53301	52818	37300	BEESTON STONEY STREET QUARRY BH.
53303	51645	38095	WOLLATON BH.
53305	51437	39236	WOLLATON MODEL FARM BH. 1 NORTH
53401	56515	37985	CLIFTON COLL. NO. 1 SHAFT
53404	58442	35235	CLIFTON COLL. 16'S MAIN GATE
53402	58866	35841	CLIFTON COLL. 8'S MAIN DEEP HARD BH.
54103	53171	43995	BABBINGTON COLL. INTAKE DRIFT
54106	53610	41130	BEECHDALE ROAD BH.
54107	50532	41494	CATSTONES UGBH.
54108	51098	41835	COSSALL COLL. DEEP HARD 40'S BH.
54109	52646	44476	HEMPSHILL COLL. STONE HEADING
54110	50100	44180	KIMBERLY COLL. NO. 1 SHAFT

54111	50621	40043	MOOR FARM BH.
54112	54975	41004	RADFORD COLL. DC. SHAFT
54113	54986	40750	RADFORD COLL. S LEVEL UGBH. 7
54114	54145	40768	RADFORD COLL. UGBH. 8
54115	51590	42558	SEAGRAVE BH.
54116	52078	40349	WOLLATON COLL. NO. 1
54101	53238	40412	WOLLATON COLL. NO. 4
54301	51904	46169	BABBINGTON COLL. 19'S UGBH. 1
54304	51869	48960	BABBINGTON COLL. 2'S MAIN INBYE BH.
54302	52205	47555	BABBINGTON COLL. DEEP SOFT 2'S UGBH. 3
54306	54029	48995	HUCKNALL NO. 2 COLL. NO. 5 SHAFT
54307	50720	46160	MOOR GREEN COLL. WATERLOO 3'S UGBH.
54312	52701	48021	HUCKNALL NO. 1 COLL. NO. 2 SHAFT
54401	55623	47454	BESTWOOD COLL. UGBH. 4
54402	57435	49126	BESTWOOD COLL. UGBH. 8
54403	59799	45960	GEDLING COLL. TOP HARD 11'S/12'S JN. BH.
54404	56389	49420	GOOSEDALE FARM BH.
55101	51773	53287	ANNESLEY COLL. NO. 1 SHAFT
55102	50657	52422	ANNESLEY COLL. UGBH. B4
55103	53647	50195	LINBY COLL. UGBH. 2
55104	54683	52130	PAPPLEWICK HALL BH.
55201	57576	53938	NEWSTEAD COLL. UGBH. 2
55202	56308	53313	KIGHILL BH.
55203	55487	51049	PAPPLEWICK FOREST LANE BH.
55301	52496	58550	CAULDWELL BH.
55302	51286	59517	KING'S MILL SURFACE BH.
55304	50415	57101	KIRKBY COLL. NORTH PIT
55305	52808	56372	KIRKBY COLL. UGBH. K1
55306	51458	57158	KIRKBY COLL. UGBH. K5
55401	59243	56602	BLIDWORTH COLL. BH.
55402	56600	57400	LINDHURST COLL. UGBH.
55403	55145	55065	NEWSTEAD COLL. UGBH.
55404	56953	55405	FISHPOOL BH.
56101	53110	61660	SHERWOOD COLL. DEEP SOFT DRIFT NO. 2
56102	52687	61200	SHERWOOD COLL.
56103	52092	60483	SHERWOOD COLL.
56201	59542	63105	CLIPSTONE COLL. UGBH.
56202	57390	61290	MANSFIELD COLL. UGBH.
56208	57202	61450	MANSFIELD COLL. DRIFT + BH.
56204	59542	60017	RUFFORD COLL. NO. 2 SHAFT
56301	50890	69490	CROSS HILLS BH.
56302	50170	66043	PLEASLEY COLL. UGBH. B1
56303	53034	67101	SHERWOOD COLL. NO. 1 DRIFT
56304	52518	68308	SHIREBROOK COLL. 5'S JN. UGBH.
56305	53360	65540	SHIREBROOK COLL. 24'S BH.
56306	54620	68460	WARSOP COLL. UGBH. 3
56401	55890	69060	WARSOP MAIN COLL. 1942 DRIFT
56402	55800	67100	WARSOP MAIN COLL. UGBH. 2
57101	52288	73606	CRESWELL COLL. NO. 2 SHAFT UC.
57102	50540	73180	ELMTON GREEN BH.
57103	54500	74500	HOLBECK HENNYMOOR FARM BH.
57104	52900	70500	LANGWITH COLL. UGBH.

57105	50700	74800	MARKLAND GRIPS BH.
57106	52820	72060	NORWOOD FARM BH.
57201	58020	70041	WELBECK COLL. BH.
57302	51500	77100	DALE INN BH.
57304	53411	75765	WHITWELL COLL. NO. 2 SHAFT
57401	58500	77580	MANTON COLL. UGBH. 5
57402	55190	78310	STEETLY COLL. UGBH. 1
58101	54600	84100	DINNINGTON COLL. UGBH. 2
58201	59910	81400	FOREST HILL BH.
58202	58930	83404	WIGTHORPE BH.
58301	51020	85340	DINNINGTON COLL. UGBH. 1
58302	54720	87200	DINNINGTON COLL. UGBH. 3
58303	52480	89940	THURCROFT COLL. UGBH. 7
58401	58450	87065	FIRBECK MAIN COLL. UGBH. 1
58402	58848	88873	FIRBECK MAIN COLL. UGBH. 2
63102	64161	33841	CLIPSTONE MILL LANE BH.
63103	64892	34335	COTGRAVE WOLDS BH.
63104	61719	32889	PLUMTREE EAST BH.
63106	61938	33587	PLUMTREE HOE HILL BH.
63107	61105	33448	PLUMTREE NORTH BH.
63201	66900	33368	OWTHORPE BH.
63301	61228	37224	BASSINGTON BH.
63302	63840	36690	COTGRAVE BRIDGE BH.
63303	64939	35949	COTGRAVE SOUTH BH.
63304	60430	35800	EDWALTON BH.
63305	60312	37744	GAMSTON BRIDGE BH.
63306	61219	38668	HOLME GRANGE BH.
63307	63068	39322	HOLME PIERREPORT BH.
63308	60020	36400	WEST BRIDGEFORD LEADHURST ROAD BH.
63401	65113	36420	COTGRAVE COLL. PILOT HOLE
63402	65271	36849	COTGRAVE NORTH BH.
63403	68778	35121	CROPWELL BISHOP NO. 1 OIL WELL
63404	68135	38695	CROPWELL BUTLER NO. 1 OIL WELL
63405	66570	36190	FOSSE WAY MANN'S BRIDGE BH.
63406	66488	39815	HARLEQUIN BH.
64103	63465	44846	GEDLING COLL. B11'S UGBH.
64106	63016	43745	GEDLING COLL. B3'S HIGH HAZLES UGBH.
64201	67234	44823	GUNTHORPE GRANGE FARM BH.
64301	62180	48110	WOODBOROUGH BH.
64401	65350	47875	EPPERSTONE WASH BRIDGE BH.
64402	66520	45470	LOWDHAM GRANGE BH.
65101	62400	50800	CALVERTON THORNDALE PLANTATION BH.
65102	64445	54435	HARTSWELL FARM BH.
65103	60512	52830	SALTERFORD FARM BH.
65301	63969	55793	CARR BANK FARM BH.
66201	65260	61335	BILSTHORPE NO. 1
66202	67542	64873	WELLOW BH.
66301	63562	67595	THORESBY COLL. NO. 1 SHAFT DEEPENING
66302	63421	67622	THORESBY COLL. UGBH.
66303	61530	67333	THORESBY 10'S UGBH. 1967
66401	69880	69146	KIRTON BH.

66402	65995	67489	OLLERTON COLL. BH.
66403	67830	66990	OLLERTON COLL. 29'S UGBH. DOWN
66404	68970	66090	OMPTON BH.
67101	61420	72120	WEBECK COLL. OLD 40'S UGBH. DOWN
67201	69505	73935	BEVERCOTES COLL. 1 + 2 SHAFTS
67202	69306	71727	BEVERCOTES PARK BH.
67205	68605	73283	HAUGHTON FARM BH.
67301	60854	78160	MANTON COLL. NO. 4 SHAFT
67302	63800	76300	MANTON COLL. UGBH. 7
67401	65510	75320	APPLEYHEAD NO. 1 OIL BORE
67404	67880	76030	ELKESLEY BH.
67405	68895	76795	JOCKEY HOUSE BH.
67406	69801	75452	TWYFORD BRIDGE BH.
68101	63851	83384	BILBY BH.
68102	64874	82366	RANBY HALL BH.
68103	62790	80520	SCOFTON BH.
68201	68954	80270	BABWORTH BH.
68202	66304	83643	BARNBY MOOR BH.
68203	66375	80750	RANBY CAMP BH.
68301	61000	86900	BLYTH BH.
68302	62490	88690	NORNAY BH.
68303	64234	88144	RANSKILL BRITISH PETROLEUM NO. 1 OIL BORE
68304	64965	85595	TORWORTH JUBILEE FARM BH.
68401	68620	88980	MATTERSBY BH.
68402	65345	89096	RANSKILL BH.
69201	67610	91670	SCAFTWORTH BH.
69401	69500	95800	MISSON BH.
73101	71000	33810	CALSTON BASSET NORTH NO. 1 OIL WELL
73102	70400	31373	CALSTON BASSET SOUTH NO. 1 OIL WELL
73201	76308	31948	PLUNGAR NO. 23 OIL WELL
73301	72525	39350	BINGHAM NO. 1 OIL WELL
73302	71900	35500	LANGAR NO. 1 OIL WELL
73303	70885	36125	LANGAR NO. 6 OIL WELL
73304	70090	37178	TITHBY BH.
75201	77180	53820	KELHAM COAL BH.
76101	71353	64380	KNEESALL BH.
76301	73990	69060	EGMANTON NO. 33 OIL BORE
76302	70970	69990	FARLEY'S WOOD BH.
76303	71575	67150	LAXTON BH.
77101	70610	71630	FARLEY'S WOOD NO. 1 OIL BORE
77102	71430	73760	MARKHAM MOOR BH.
77103	70814	72295	SOUTH MILTON BH.
77104	71260	74425	WEST DRAYTON BH. 1
77201	75283	73654	DARLTON BH.
77301	71026	78103	EATON BH.
77401	76200	78850	SOUTH LEVERTON NO. 18 OIL BORE
78301	70445	85857	LOUND BH.
79101	74590	90640	GRINGLEY ON THE HILL BH.
79201	75550	91900	WALKERINGHAM NO. 1 OIL WELL

ACKNOWLEDGEMENTS

I would like to thank Professor F.H. Stewart for the provision of facilities at the Grant Institute of Geology, the University of Edinburgh. It gives me pleasure to be able to express my gratitude to my supervisors, Dr. P.McL.D. Duff and Professor E.K. Walton, for their invaluable help and guidance. Thanks are also due to Dr. B. Lovell and Dr. W. Heptonstall who kindly read part of the original manuscript, and to J. Holroyd-Doveton and D. Doff for stimulating discussion throughout the course of the research programme.

Mr. G. Armstrong, chief geologist of the National Coal Board, gave his permission for the collection of subsurface information and Mr. R.E. Elliott, regional geologist, provided facilities at the East Midlands Geological Outstation at Arnold near Nottingham. In addition, Mr. R.E. Elliott and Mr. E. Skipsey have freely given of their time and detailed knowledge during the period of this study. Mr. D.W. Turner provided essential help in solving many coal correlation problems. To all these persons I offer my sincere thanks.

Professor A.W. Skempton, Dr. M.A. Calver, Dr. L.H. Morris and Mr. F. Pritchard all kindly provided information in response to my written request. I would also like to thank my wife for her help with the production of the typed manuscript and for constructing the bibliography.

During the period of my studies for the degree of Ph.D. (1966-1969) I was in receipt of a Shell Scholarship, for which I would like to express my thanks to the Shell International Petroleum Company Limited.

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